Searches for exotic particles with IceCube

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for the IceCube Collaboration

Link to LOI

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IceCube

South Pole

IceTop Array
81 stations

IceCube Laboratory

1450m –

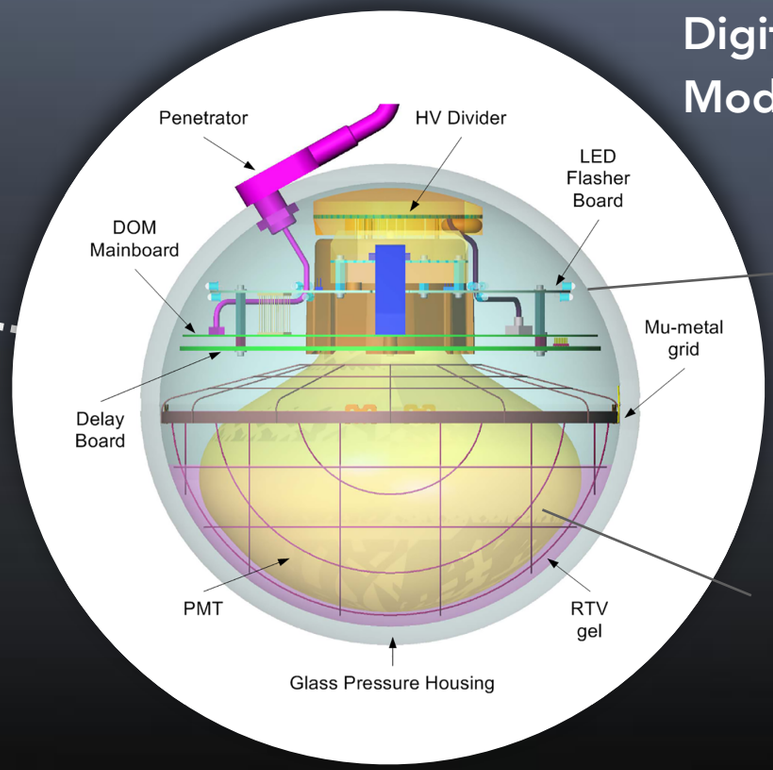
InIce Array
86 strings,
each with 60
optical sensors

2450m –

Working principle

- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Digital Optical Module (DOM)



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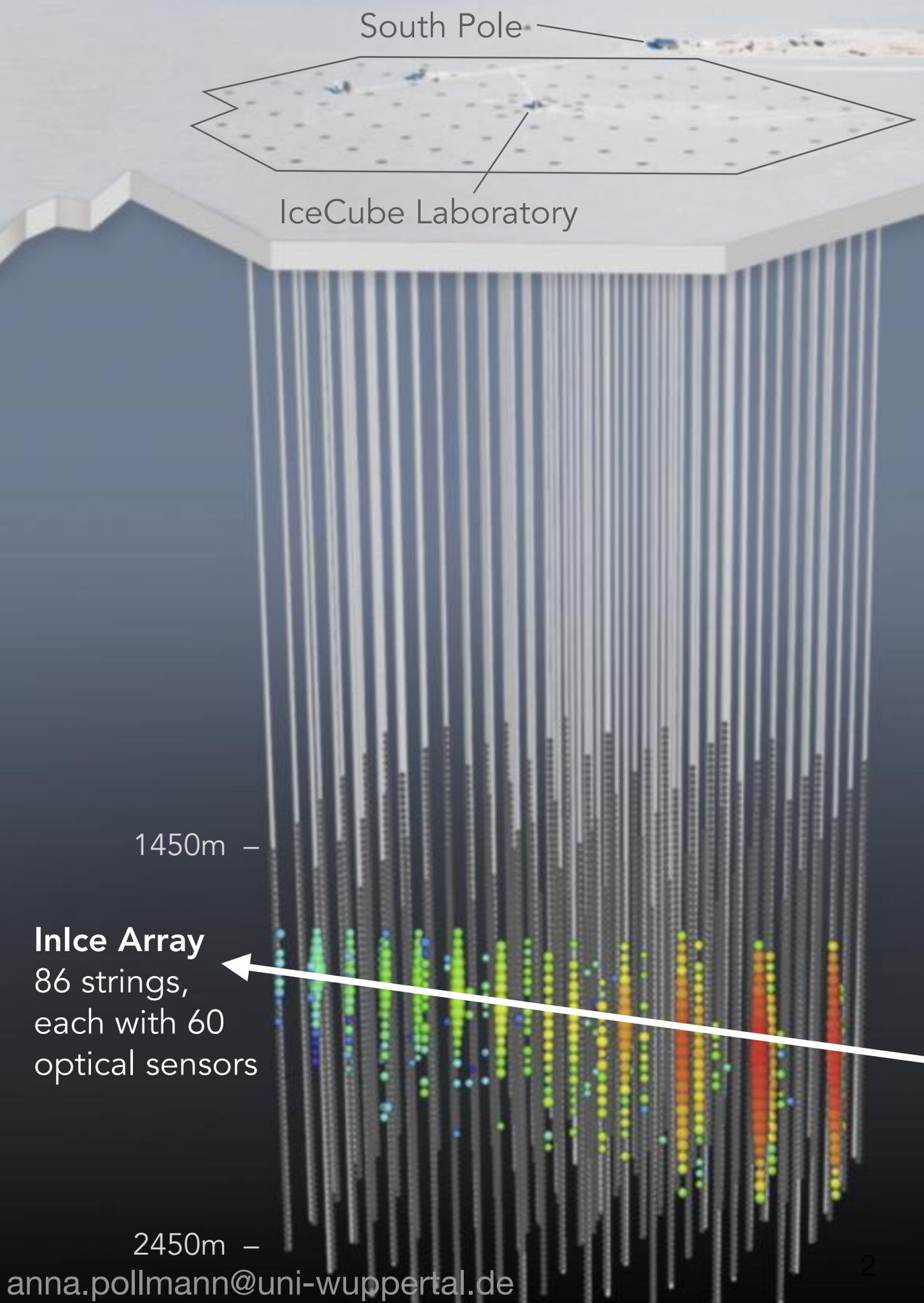
IceCube



Particle detection

- charged particles > speed of light in vacuum emit Cherenkov light

Particle types

- muons from cosmic ray air showers
- neutrinos from cosmic ray air showers (rather their interaction products)
- neutrinos from astrophysical sources

Beyond standard model physics

- indirect search using neutrinos
- direct search for distinct signatures

See:

- Dark Matter with IceCube LOI
- Neutrino Flavor with IceCube LOI

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2

Extremely massive particles

Particle

- magnetic monopoles (MM)
- Q-balls (QB)
- nuclearites (NU)

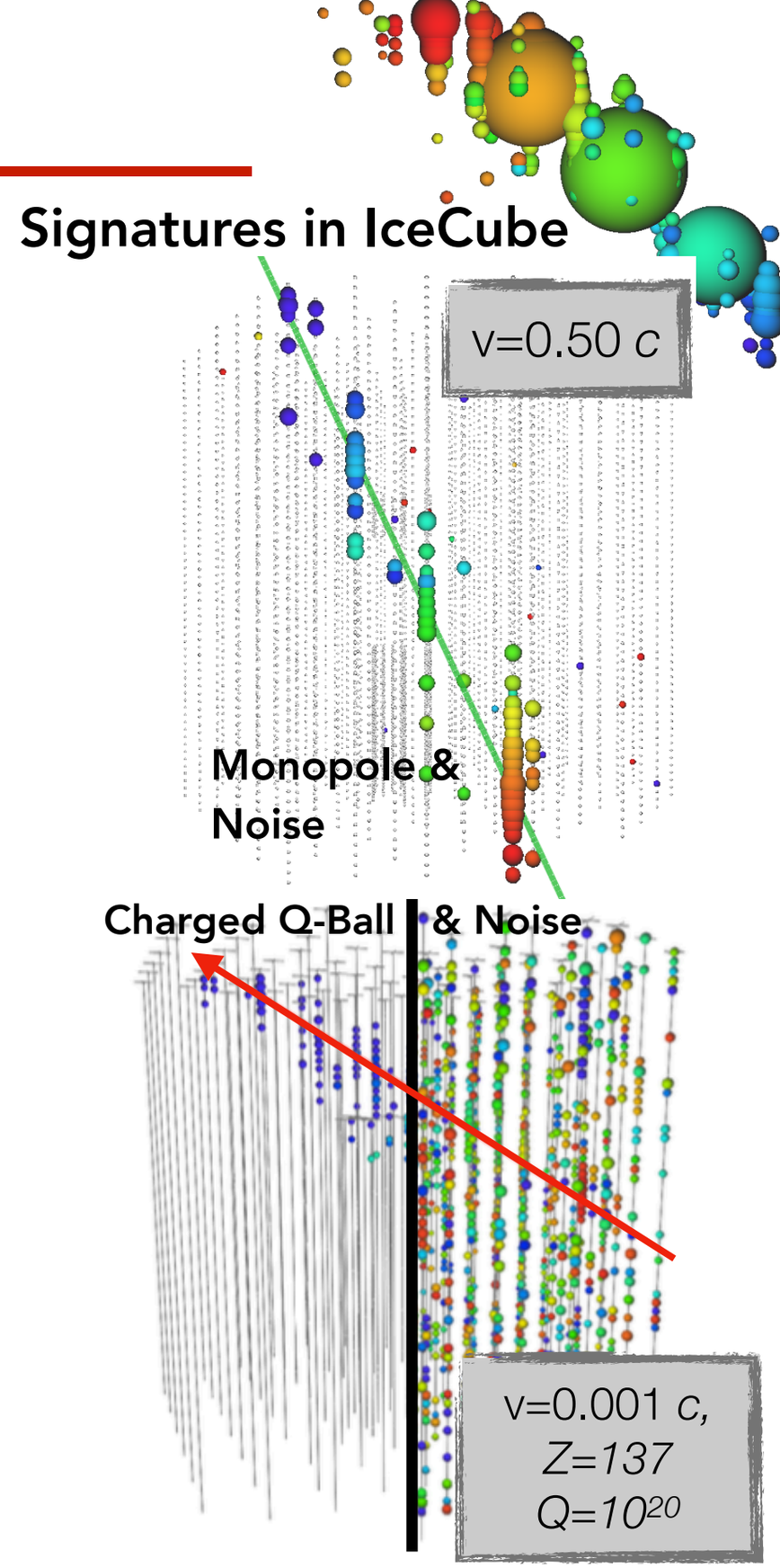
Signatures (so far)

- high speed: Cherenkov light (also indirect) (MM)
- low speed: catalysis of nucleon decay (only in some models) (MM & neutral QB)

Need detection channels for model independent searches:

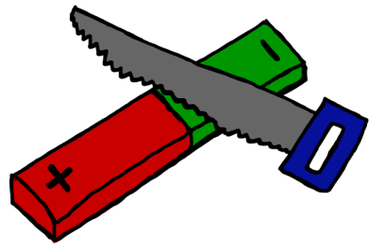
- thermal shock waves in ice (all, especially NU)
- ice luminescence
  (all, especially charged QB, slow MM)

Signatures in IceCube



Color ≙ time (red -> blue)
Size ≙ light amount

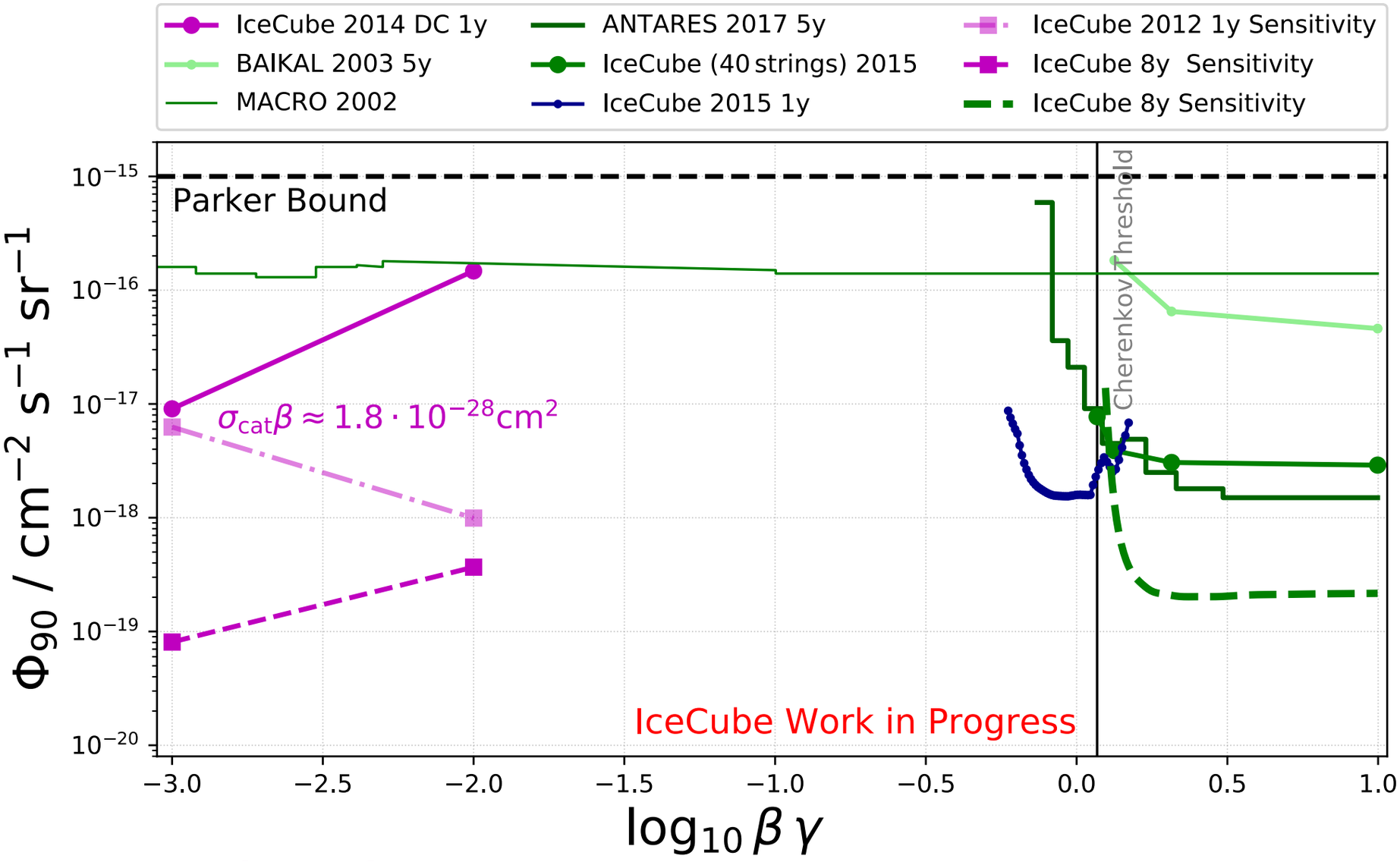
Relic Magnetic Monopoles



Current status

- multi-purpose detectors exceed specialised detectors
- IC covers a significant fraction of the parameter space

EPJ C76 (2016) 133 & EPJ C74 (2014) 2938

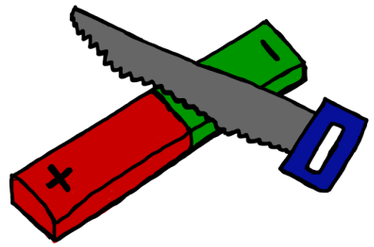


Catalysis of nucleon decay

Indirect Cherenkov radiation

Direct Cherenkov radiation

Relic Magnetic Monopoles



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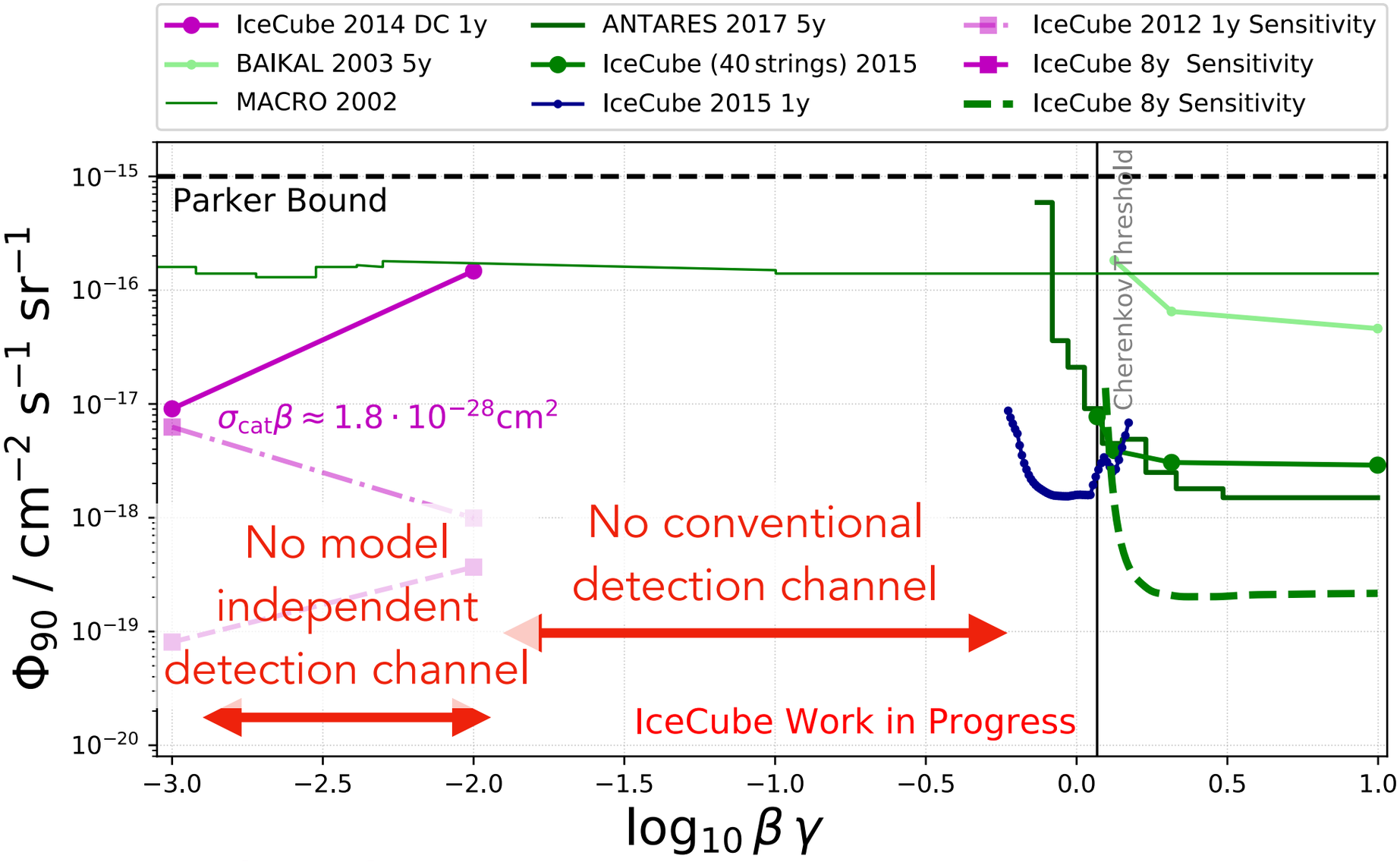

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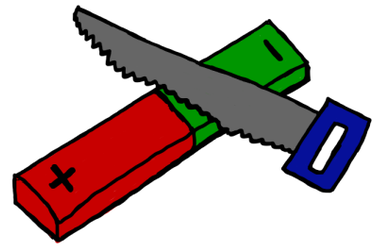

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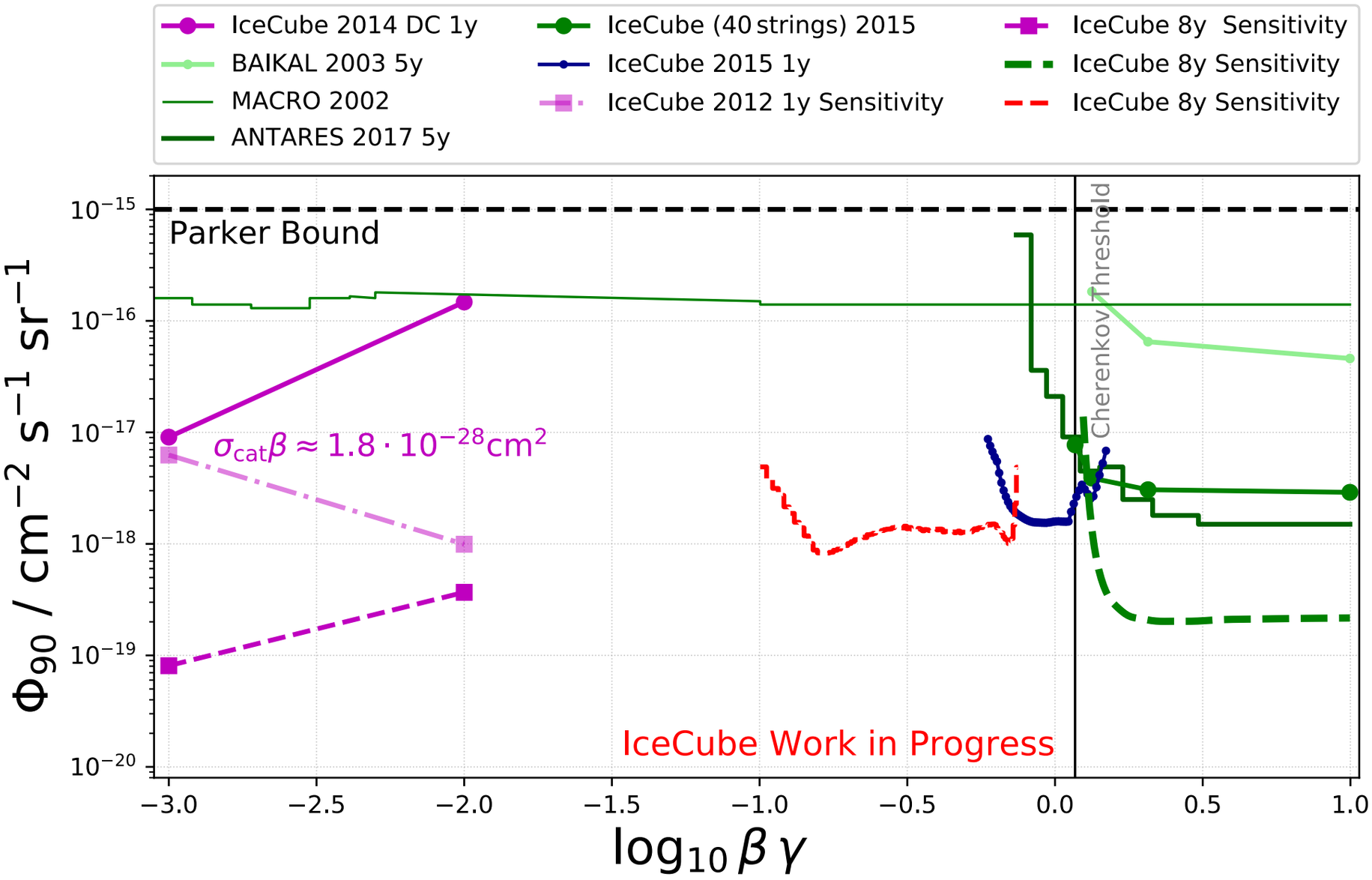
arXiv:1908.07231



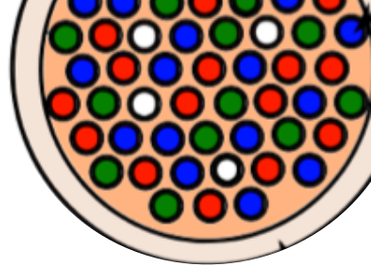
Catalysis of nucleon decay

Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Q-Balls



Current status & Outlook

Neutral:

- multi-purpose detectors best
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- scintillation detectors & heavy ion trail searches best
- IC competitive to best limits
- IC sensitivity using new luminescence channel can exceed single-purpose experiements

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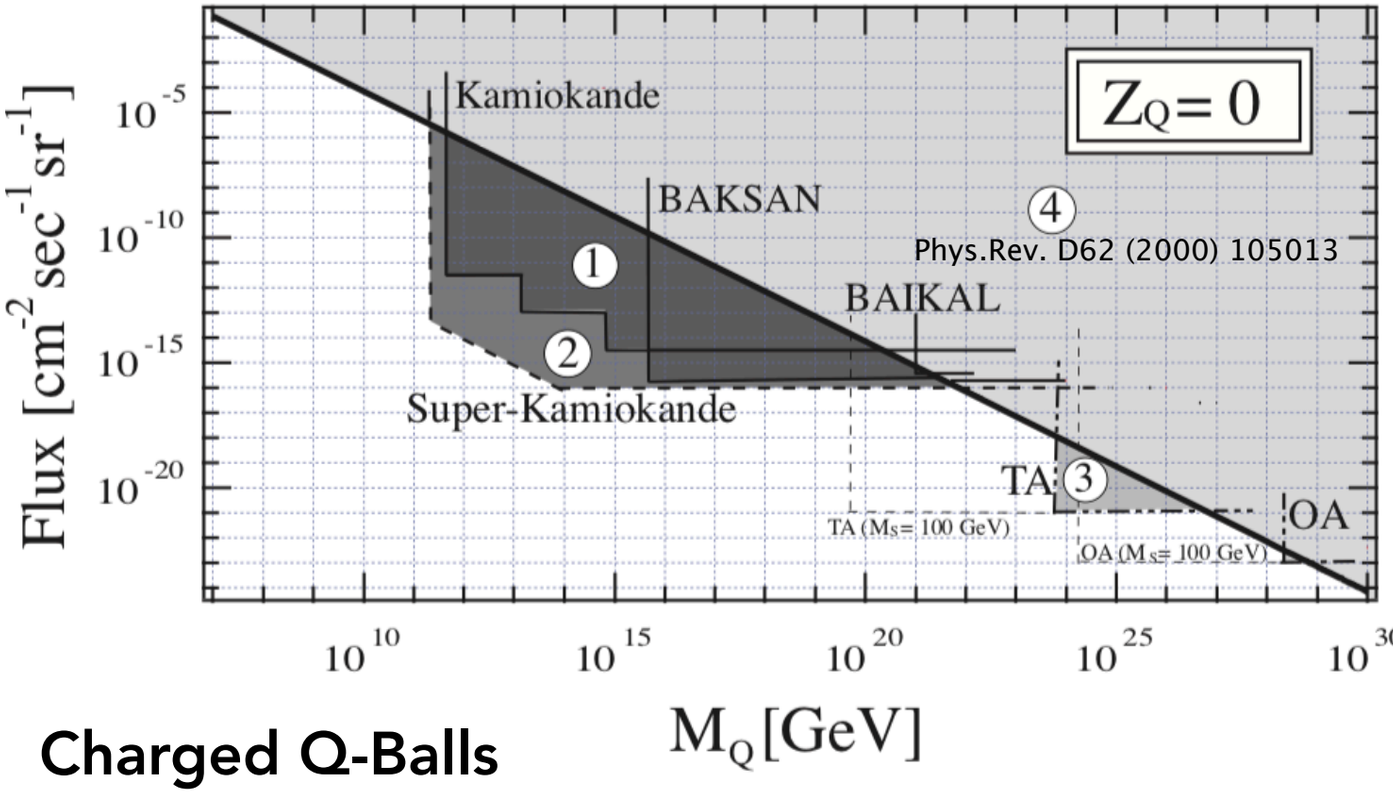

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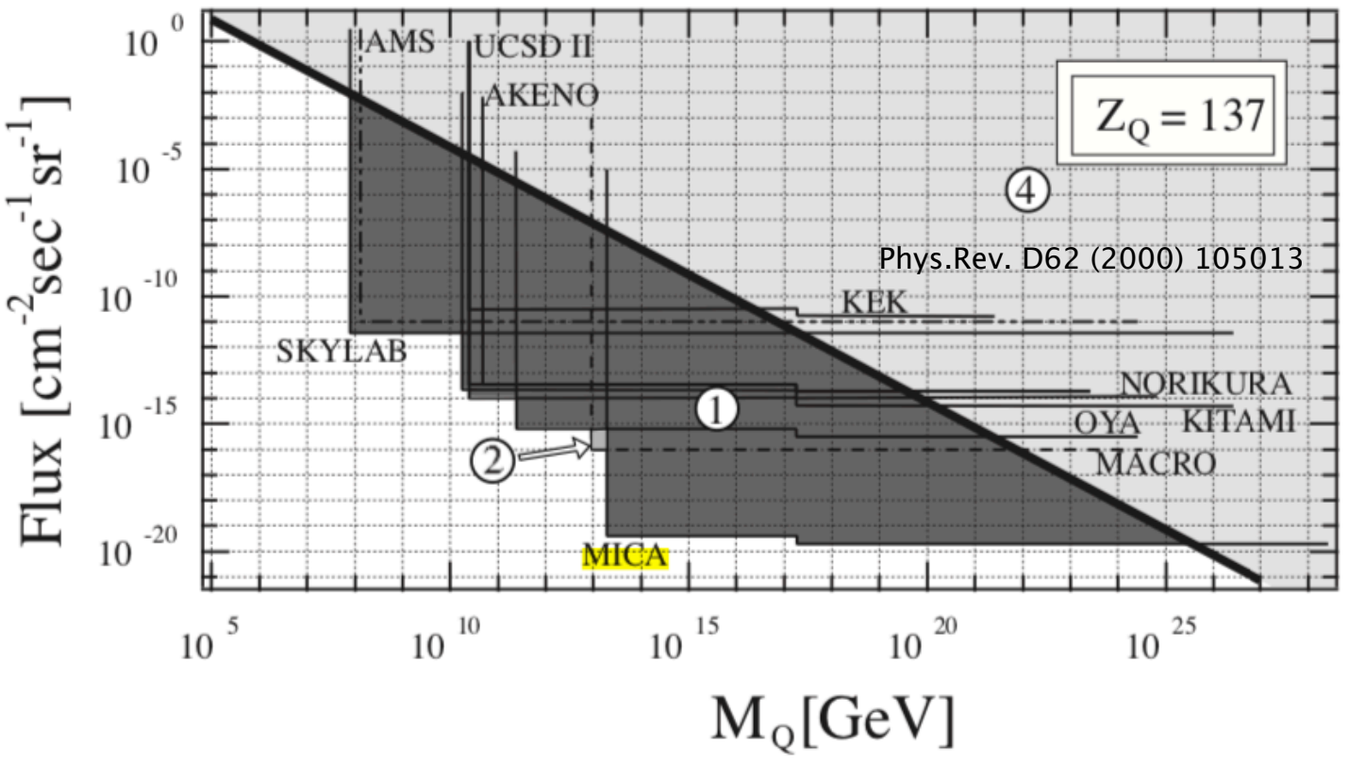

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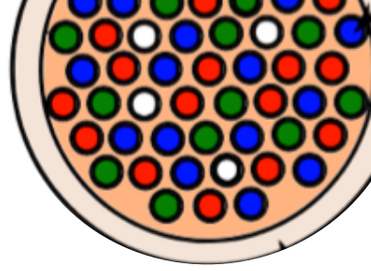

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Neutral Q-Balls

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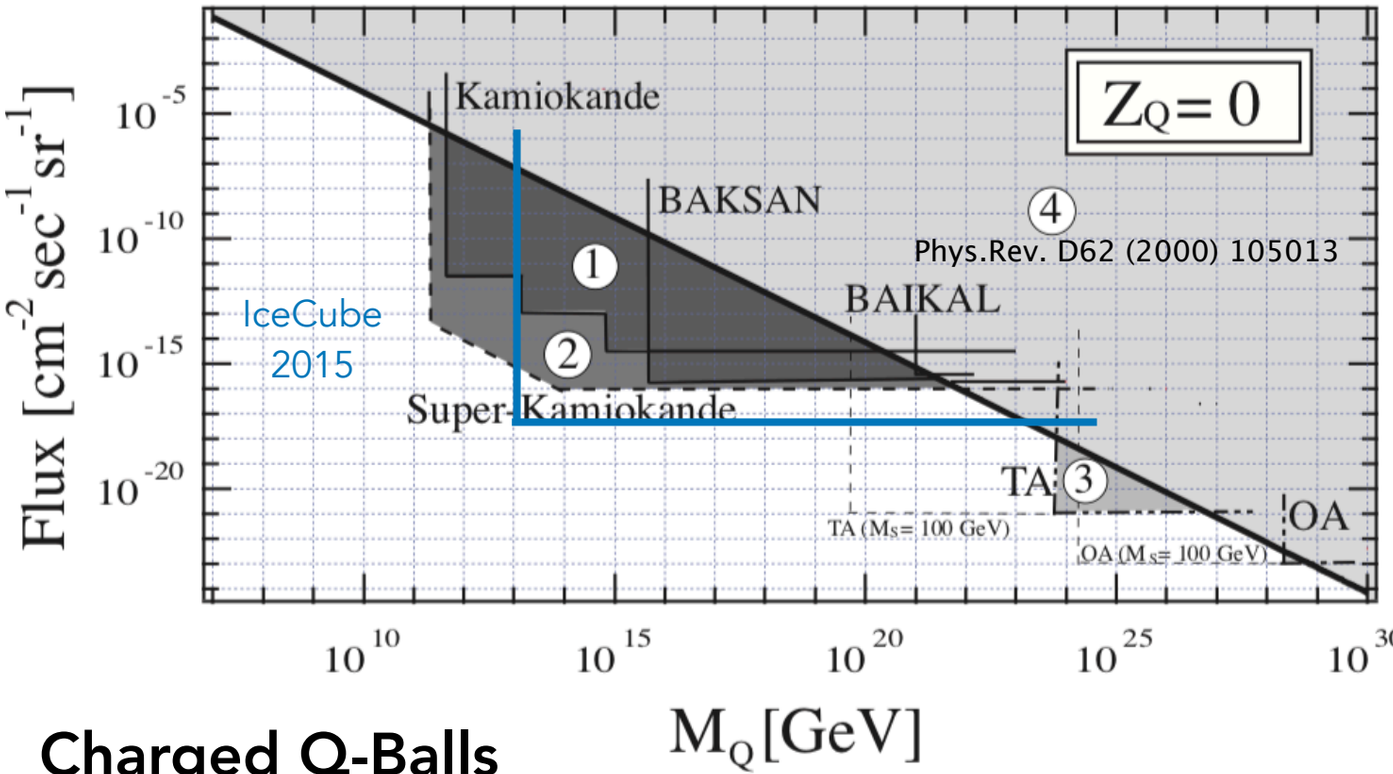

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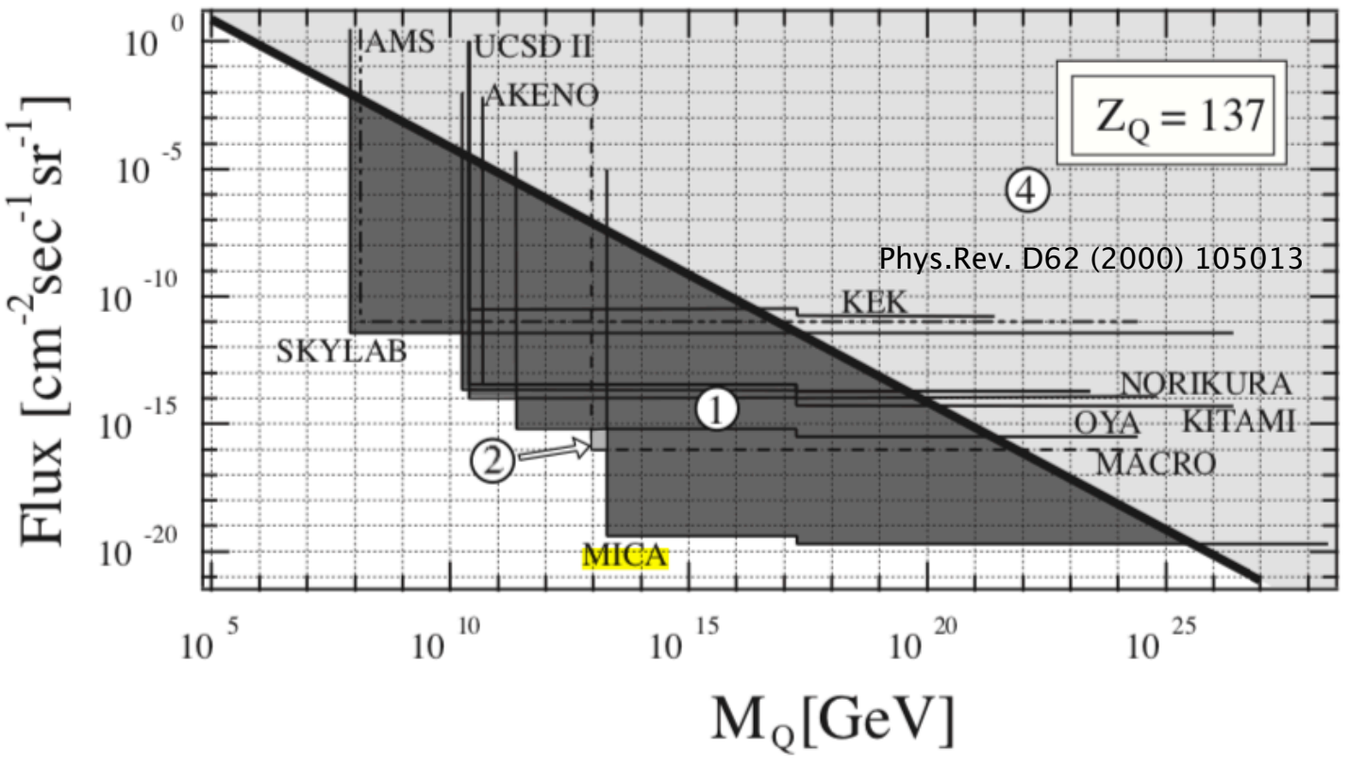

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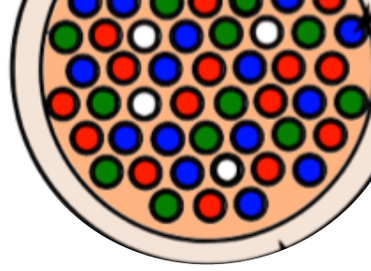

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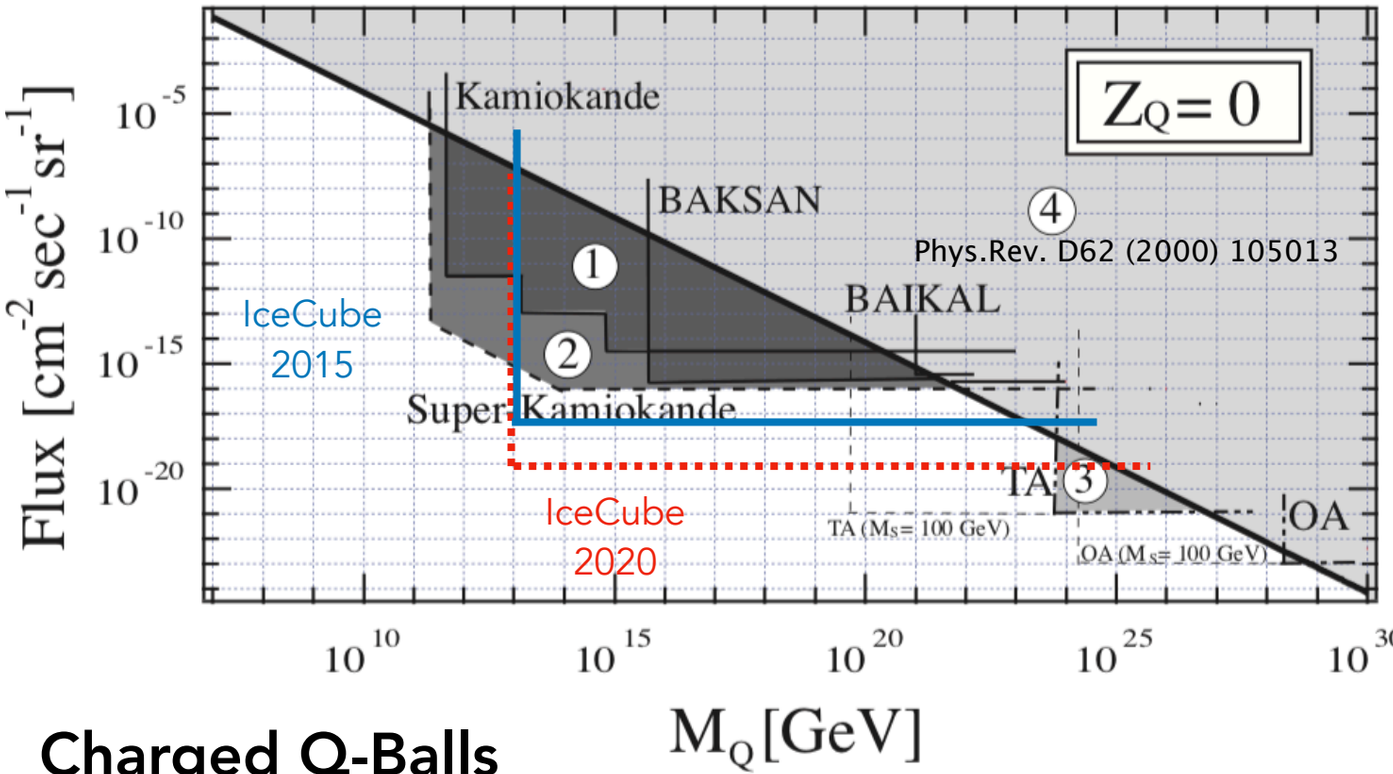

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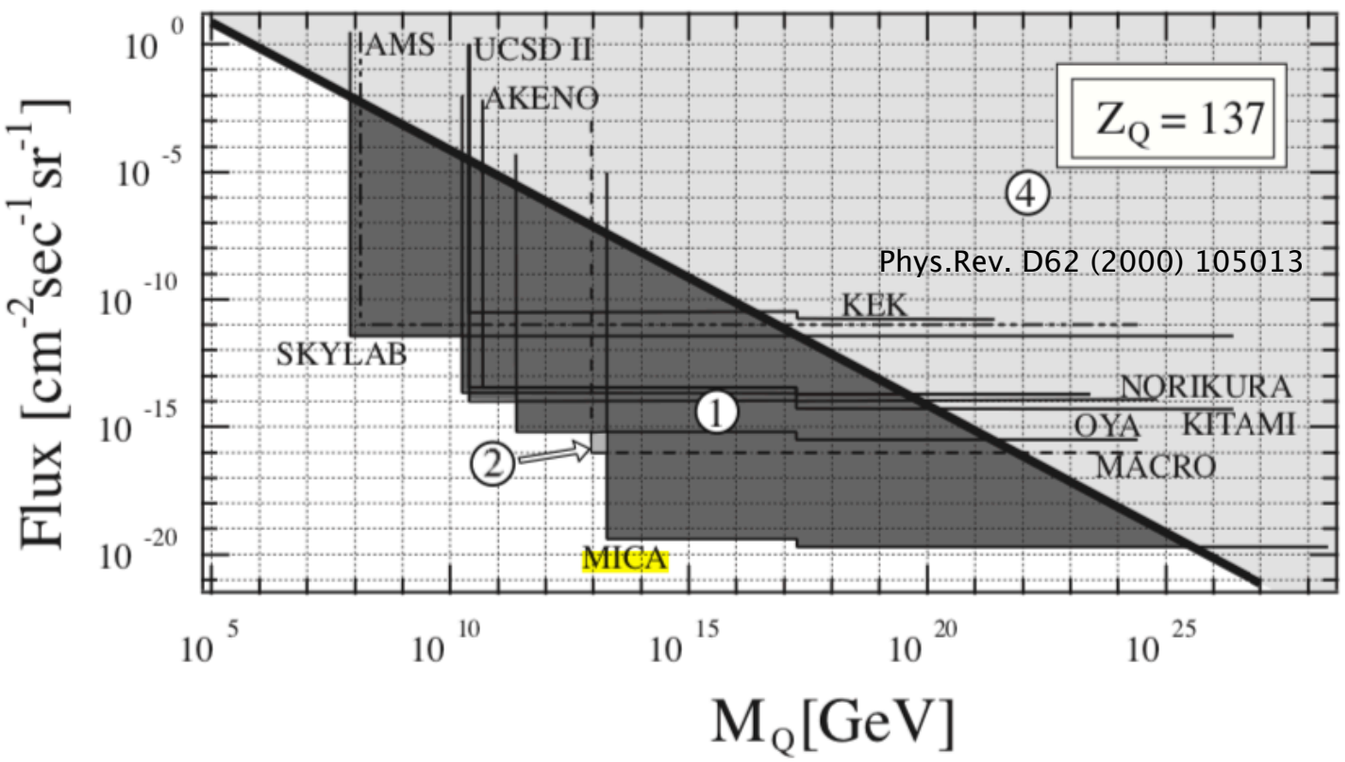
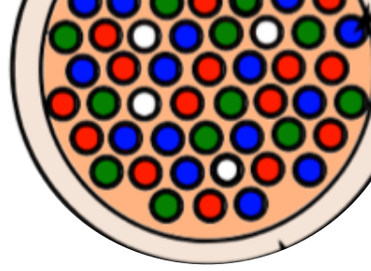


Q-Balls



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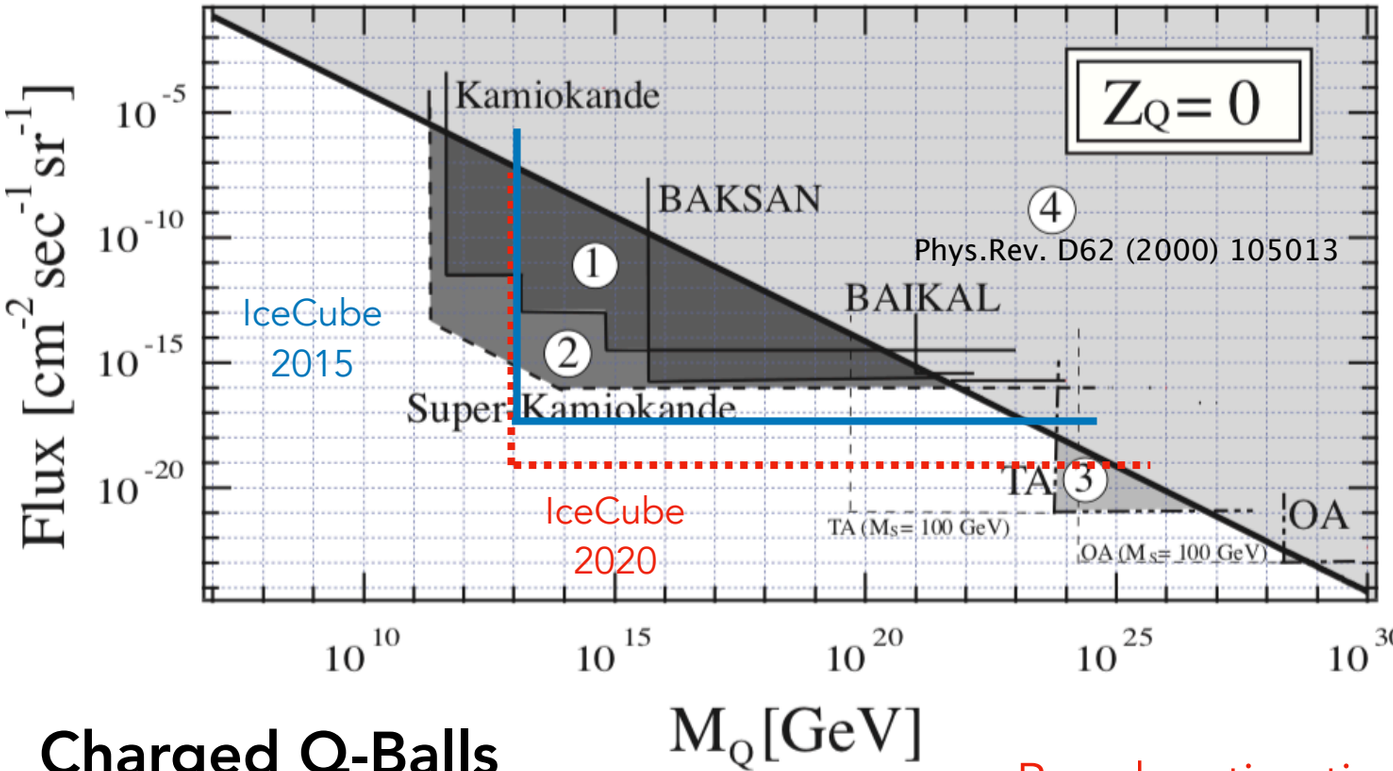
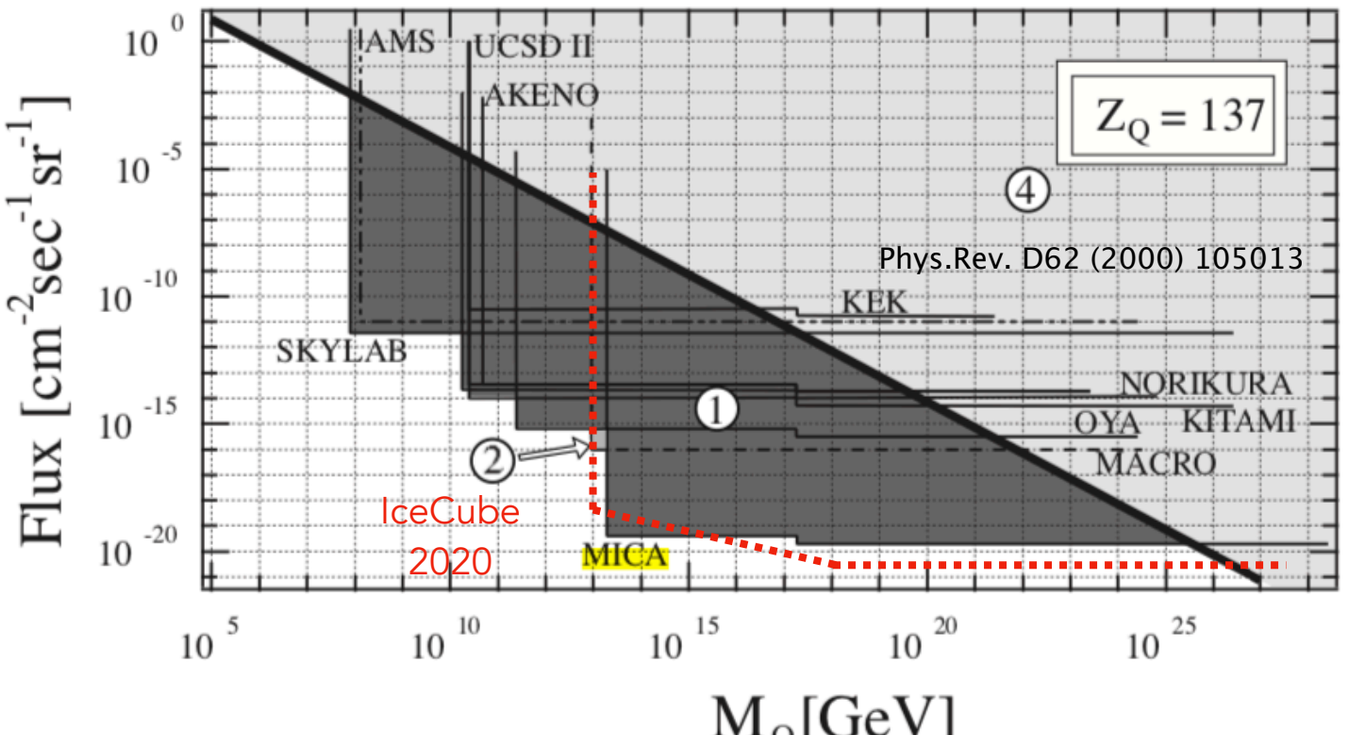


Charged Q-Balls

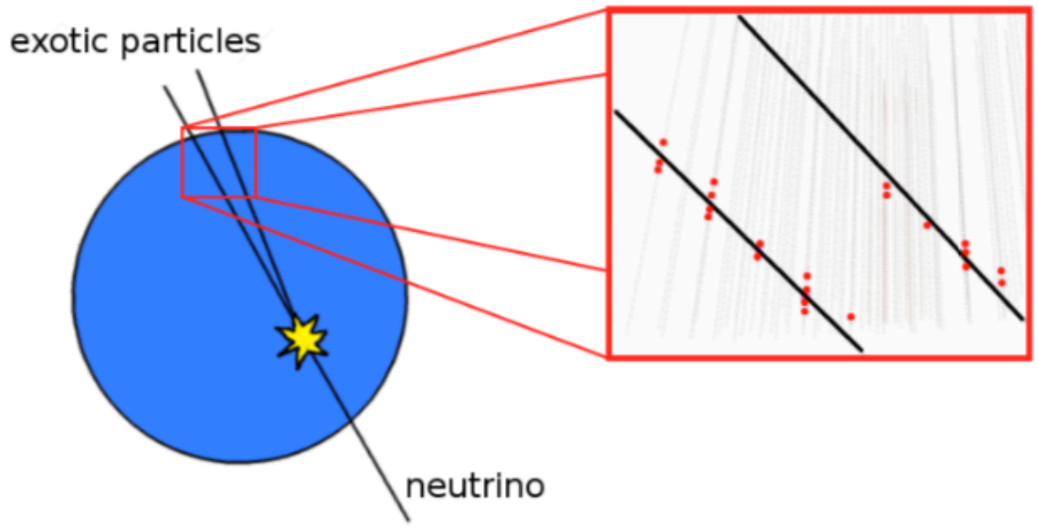
Rough estimation



Heavy long lived charged particles

Particles

- Anomalously charged particles
- CHAMPS: e.g. Staus

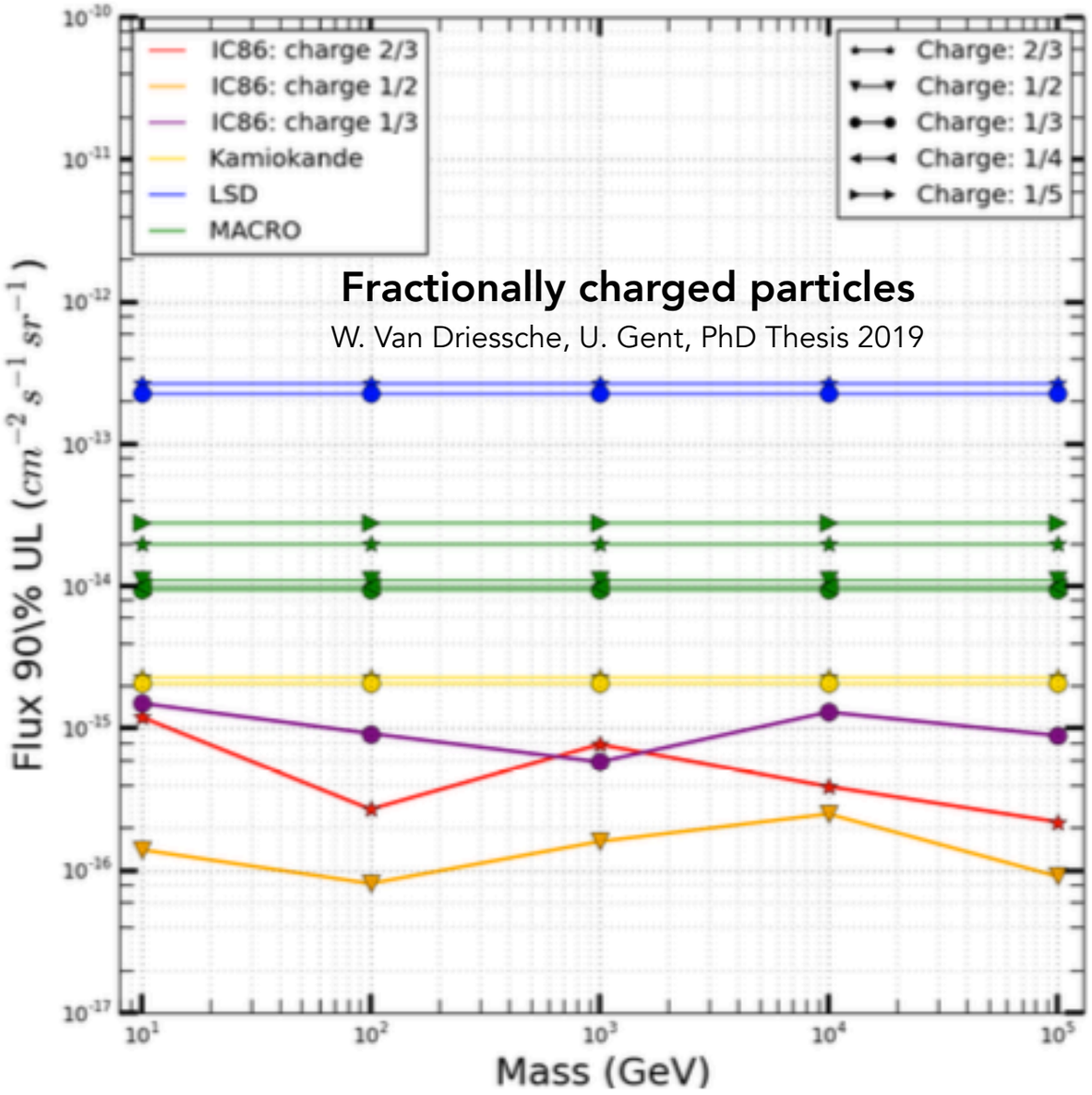


Detection

- Cherenkov light with low light emission in combination with long reach
- maybe: parallel tracks

Status

- ACP: sensitivity by IC best
- Staus: model independent search by IC, exceeded by model dependent searches at CERN



Evaporating black holes

The object

- Primordial black holes created in early Universe with m > 5×10^{14} g have their evaporation time ~ now

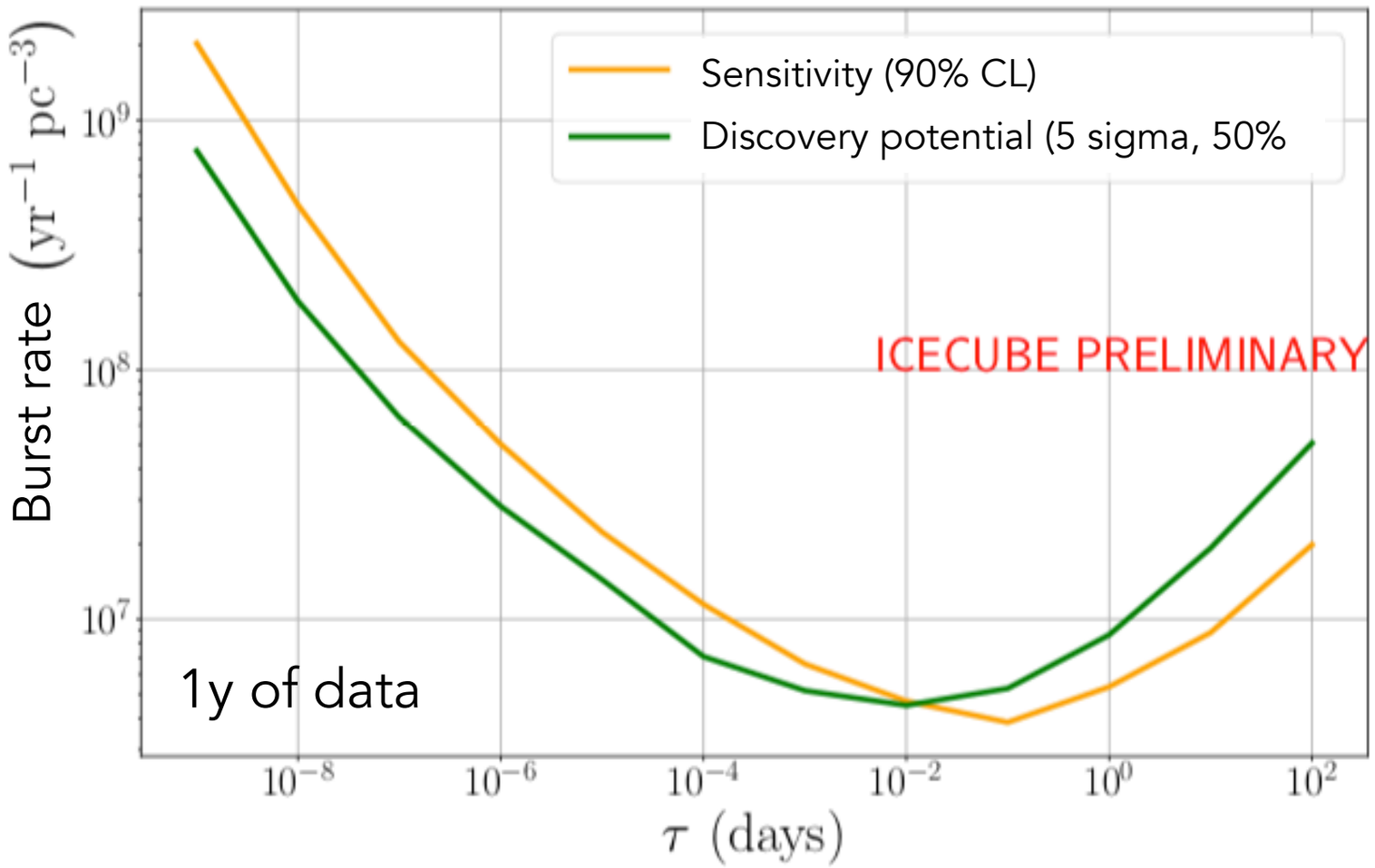
Detection

- neutrino production directly or indirectly
- distinct energy and time profile

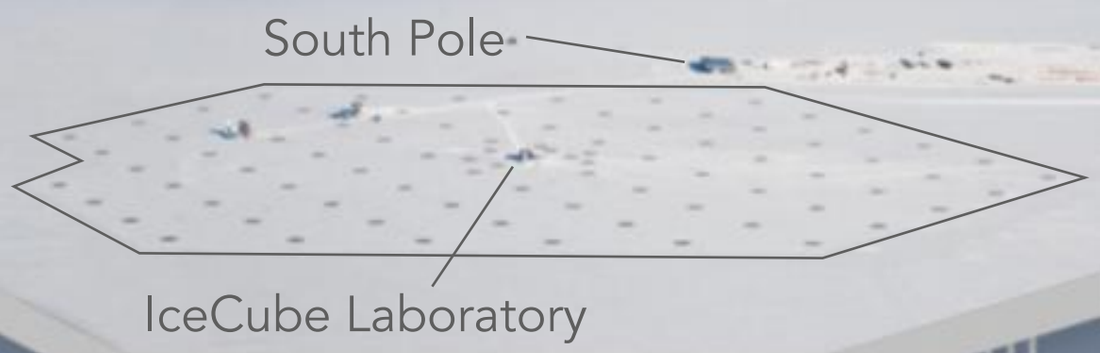
Status

- complementary to γ-ray searches
- recent models favourable for IC searches

arXiv: 1908.05403



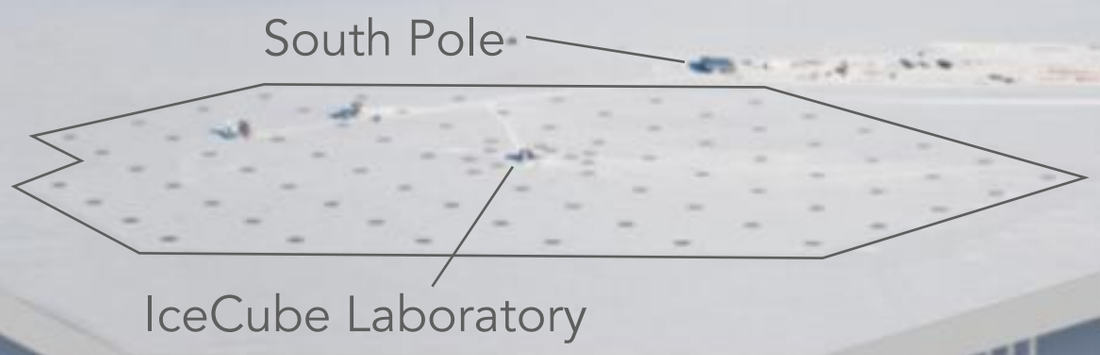
Outlook



IceCube Gen-2

- construction planned for > 2025
- increase in volume ~8
- instrumentation density reduced to ~ 1/4
- aim to gather statistics for astrophysical neutrinos

Outlook



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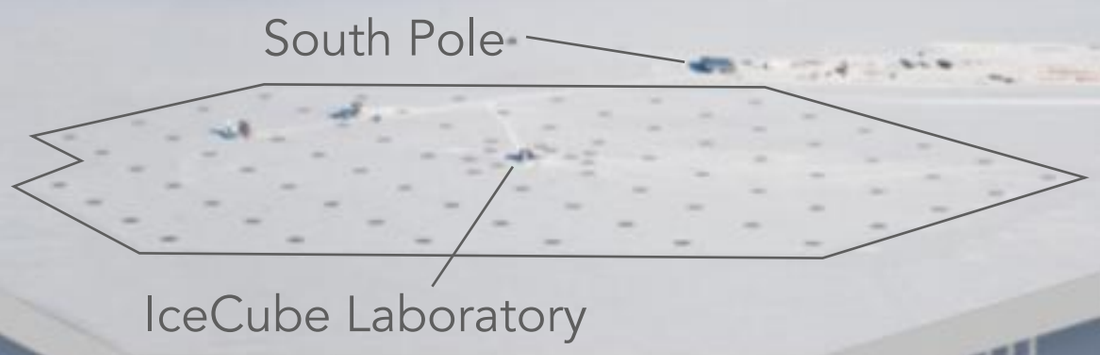

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- construction planned for > 2025
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Future prospects with Gen2

- long lived particles: increase in sensitivity with volume
- extreme heavy particles & primordial black holes: sensitivity scales ~ with volume
- luminescence ready to use and thermal shocks would increase accessible parameter space

Summary

- IC largest particle detector on Earth in instrumented volume
- precision instrument for ultra-high energy particle physics
- world-best limits or sensitivities for several exotic particles (possible)

➡Lots to discover!

- exceeding sensitivity of specialised detectors

Link to this LOI

- not only IC provides high-quality data for future analyses, but also its extensions IC-Upgrade and IC-Gen2
- many channels to probe new physics

Also see further BSM physics with IceCube:
- Dark Matter with IceCube LOI
- Neutrino Flavor with IceCube LOI

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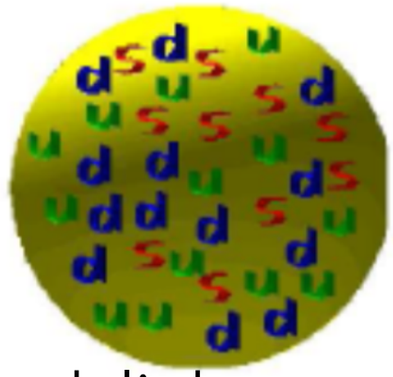
Backup

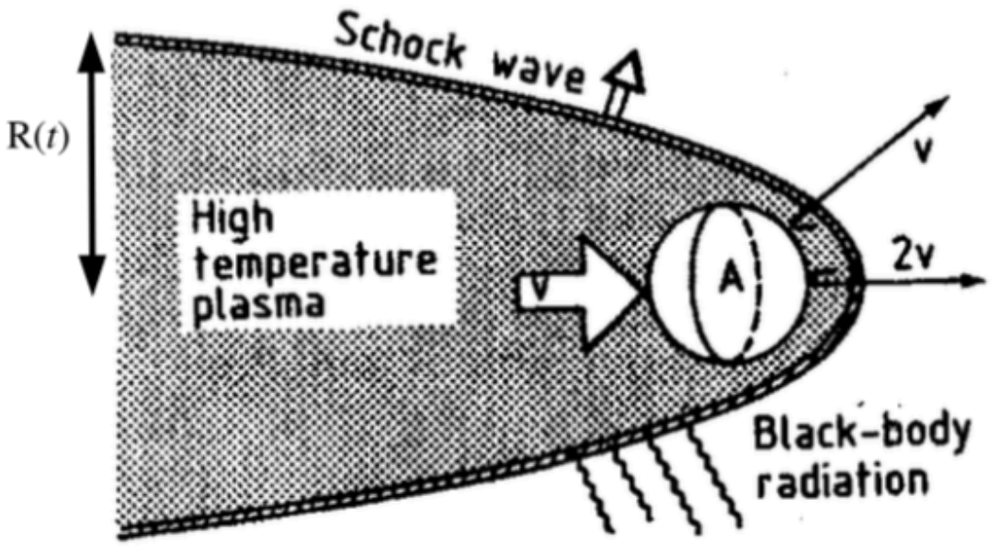
anna.pollmann@uni-wuppertal.de

Nuclearites



New detection possibility

- thermal shock wave in ice

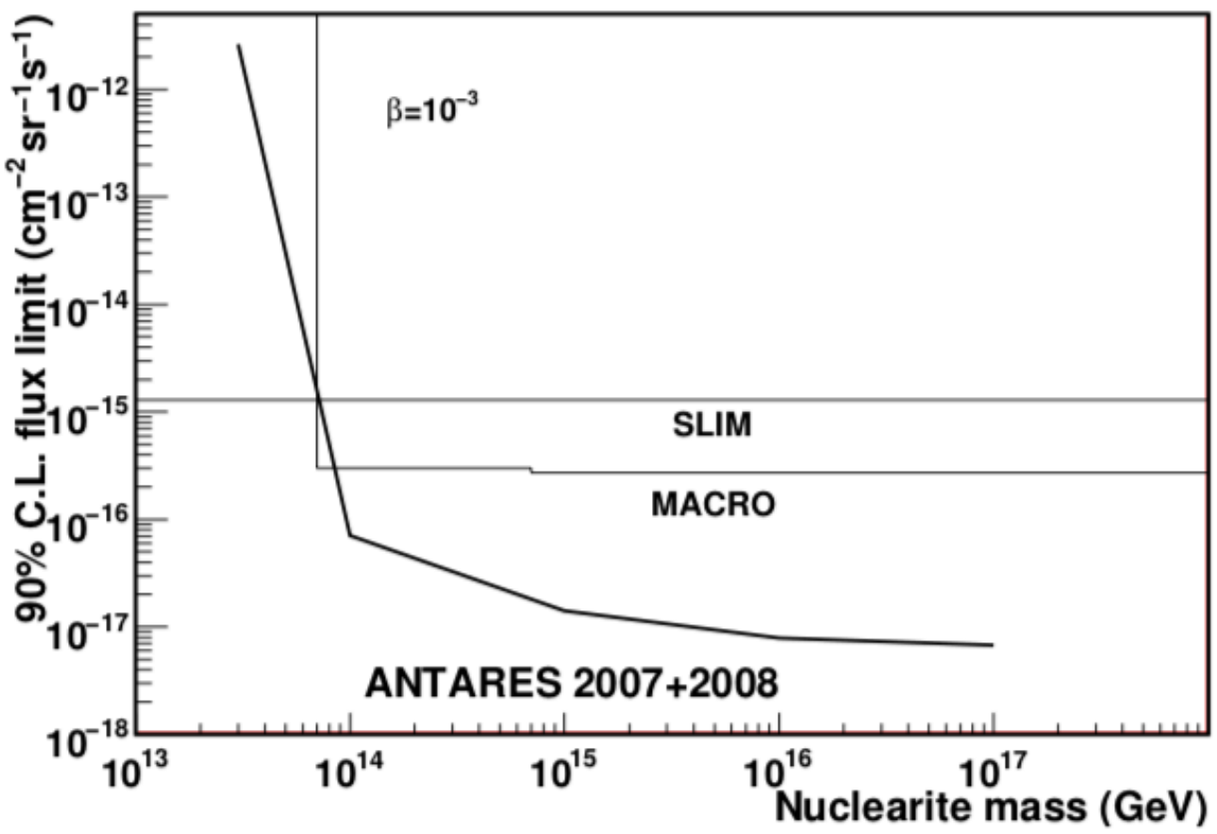


Outlook

- investigation of thermal shock light yield in ice needed
- potential of 2-3 orders of magnitude in sensitivity with IC and IC-Gen2

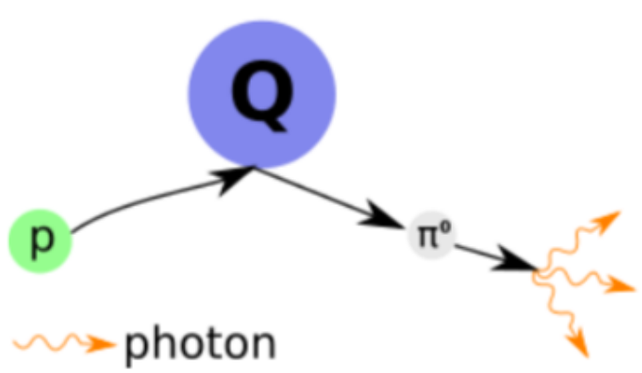
Current status

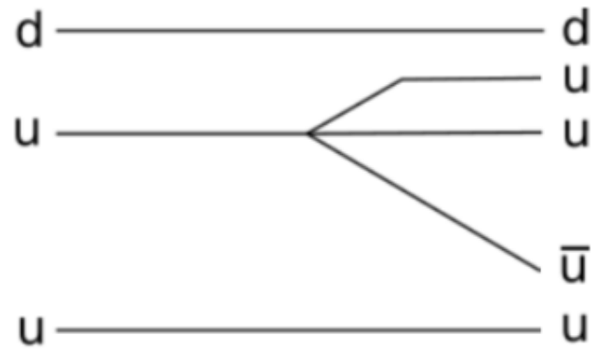
- best limit by neutrino detector
- large uncertainty in detection method



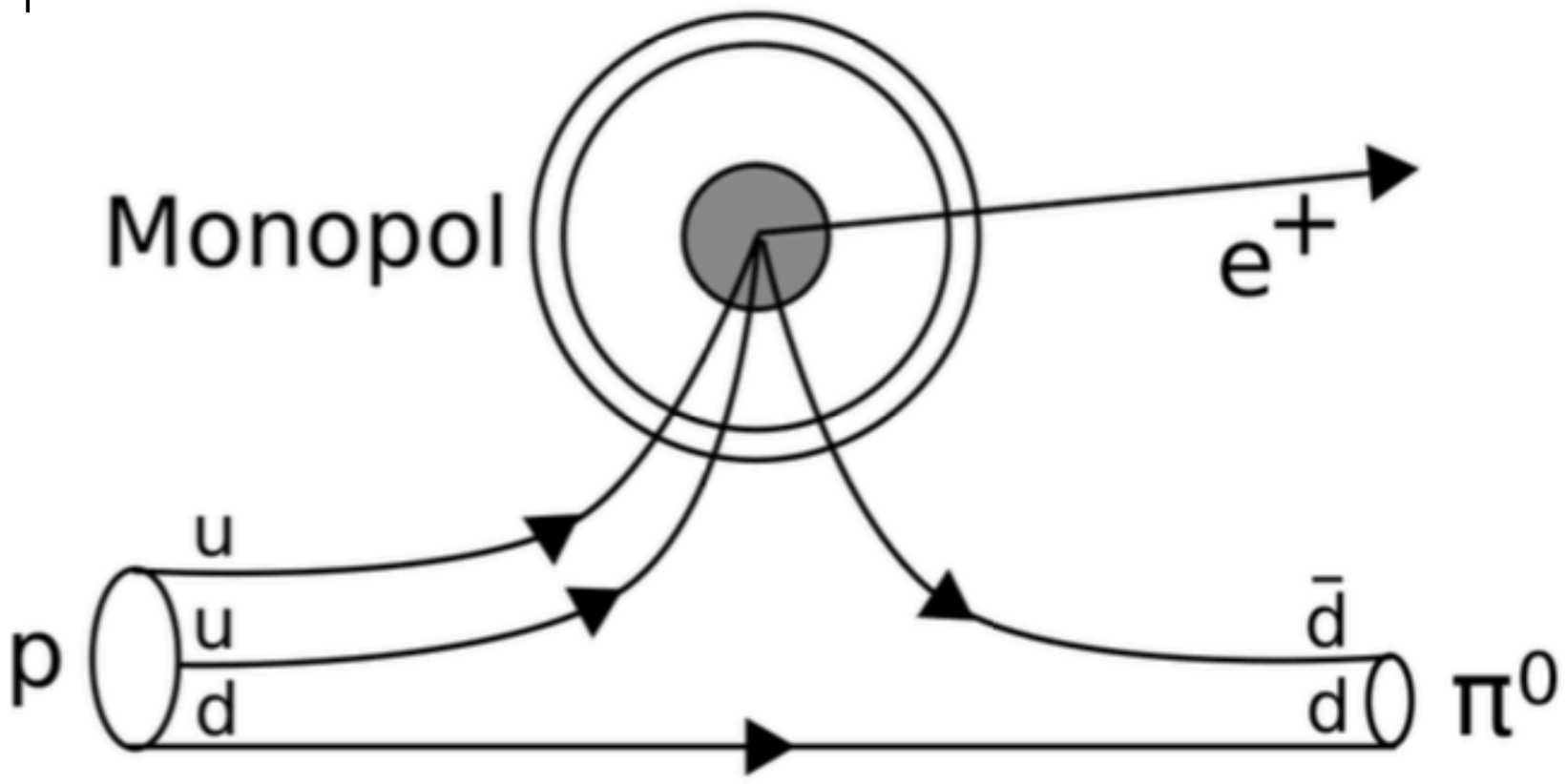
Nucleon decay

Q-Balls: KKST Process

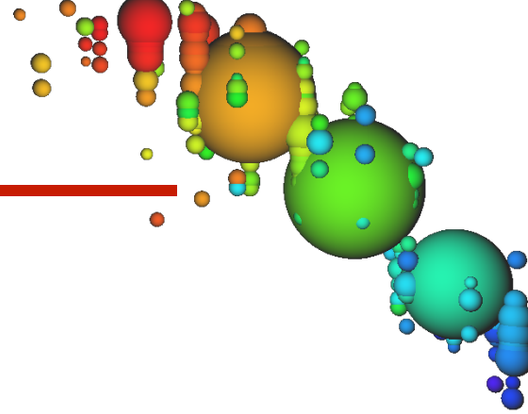




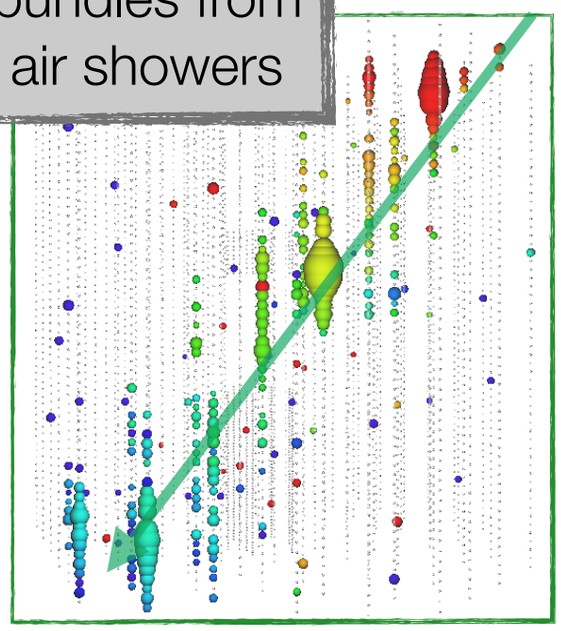
Magnetic monopoles: Rubakov-Callan

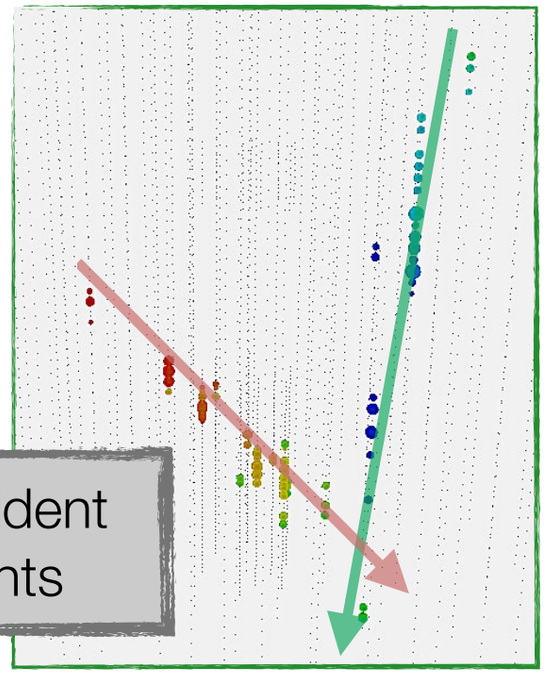


Background types



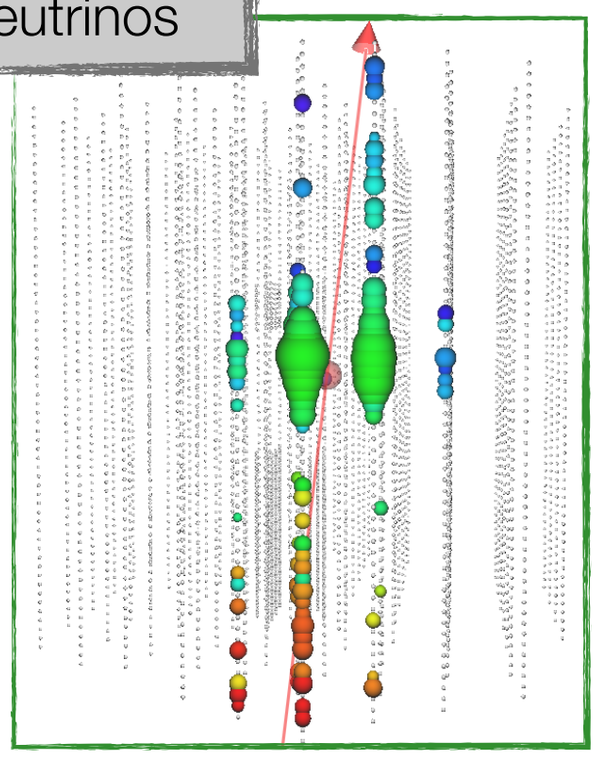
muon bundles from air showers





coincident events

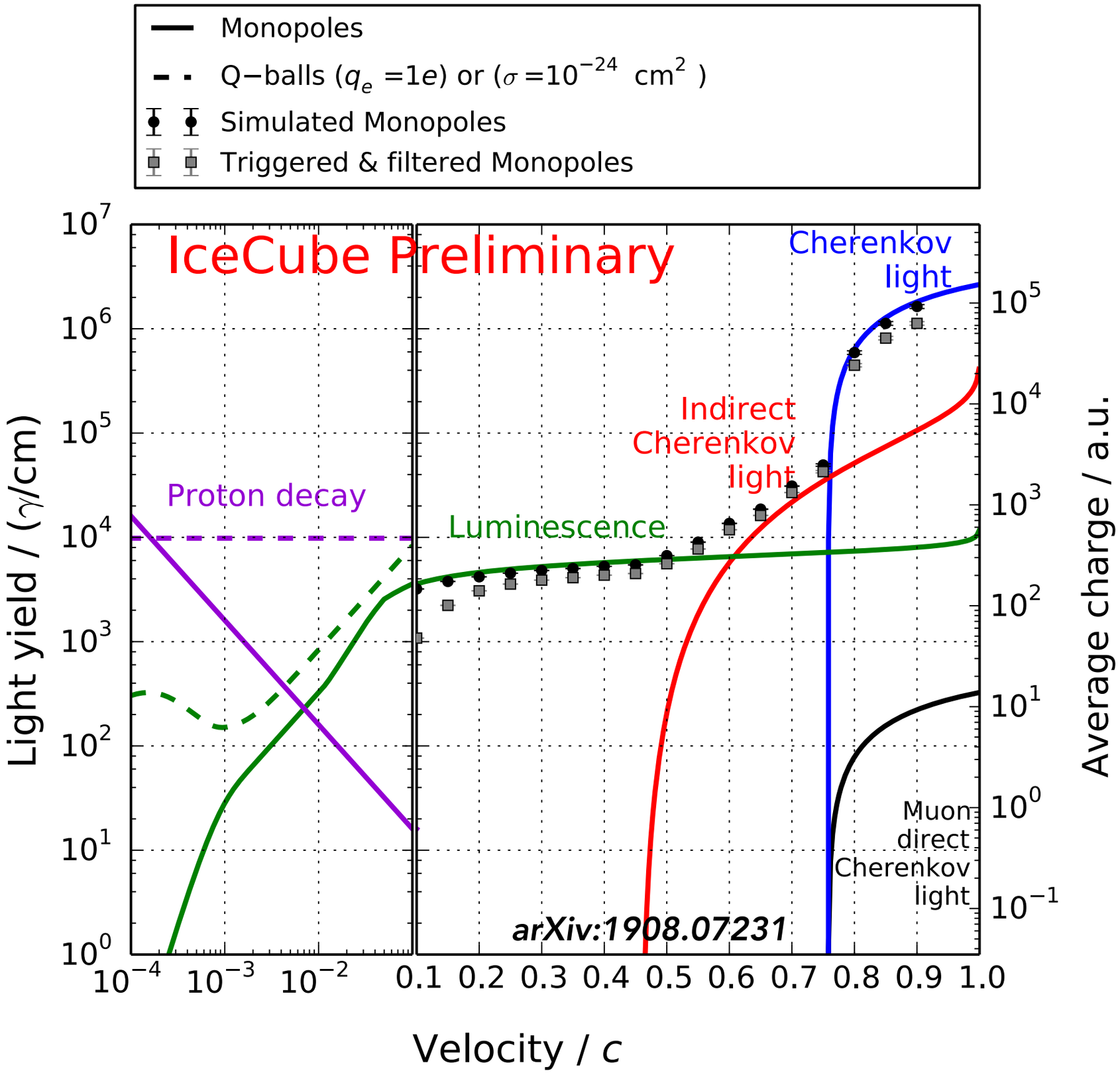
neutrinos



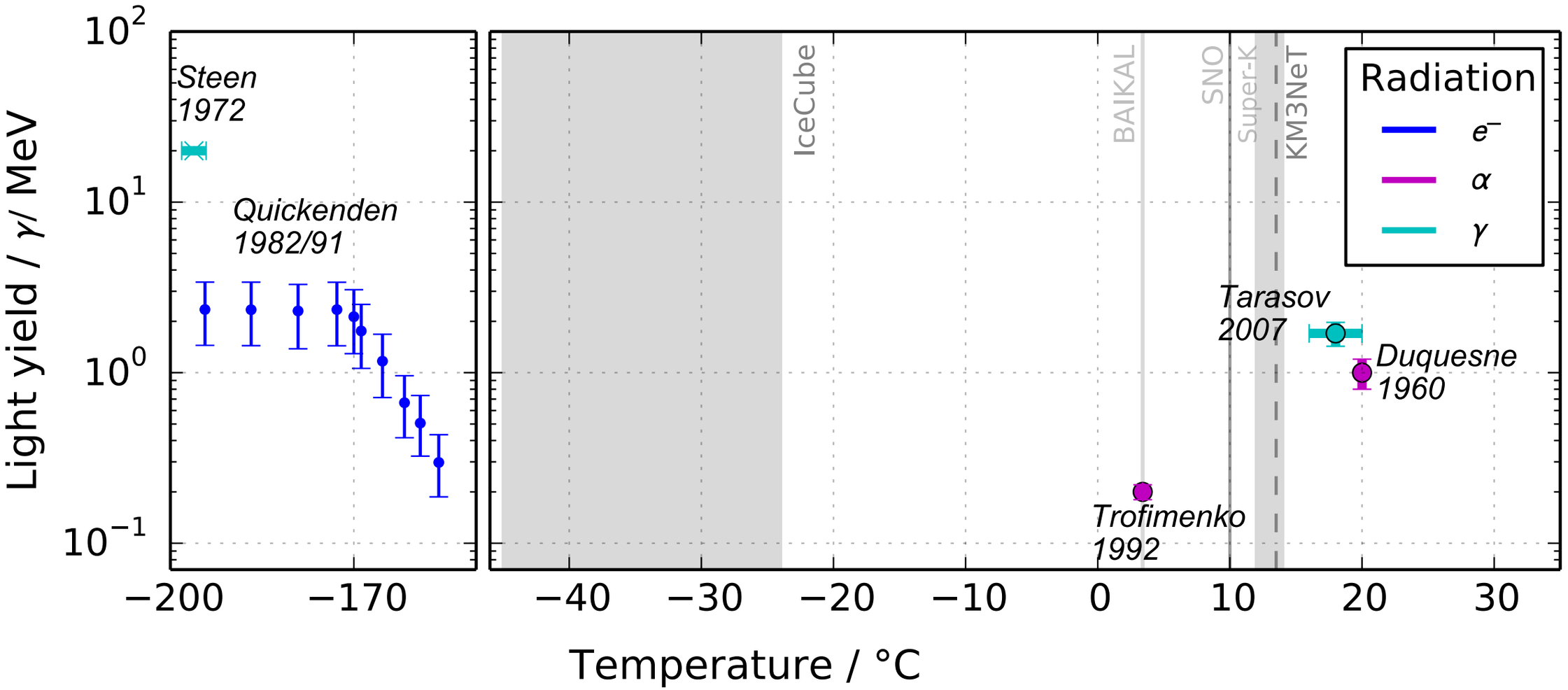
Color ≙ **time** (red -> blue)

Size ≙ **light amount**

Light production by (exotic) particles in water and ice



Previous light yield measurements



Note:

- sample quality varies significantly between measurements
- different radiation causes different amount of quenching

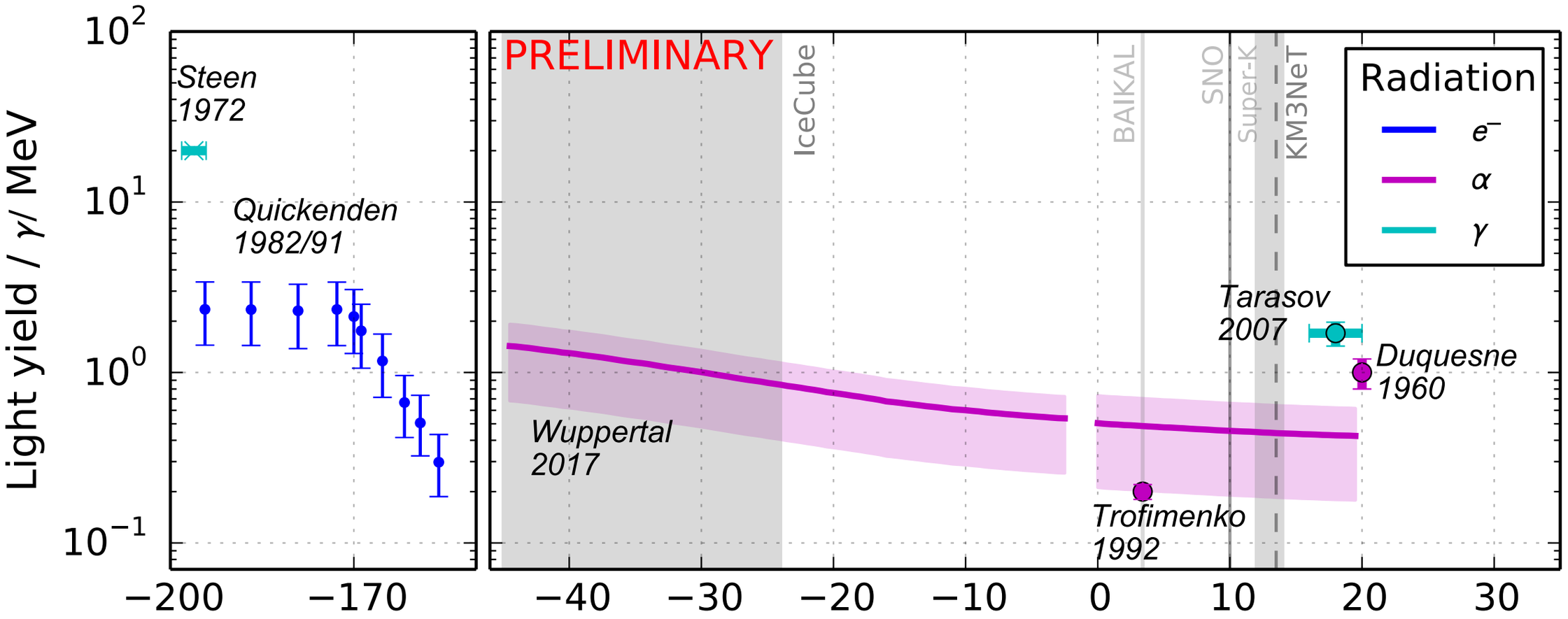
Comment:

- uncertainties of new laboratory measurement originates from water quality
- "Trofimenko" is the only in-situ measurement, all others use cleaned water

arxiv:1710.01197

Previous light yield measurements

First laboratory measurement at temperatures of neutrino telescopes



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South Pole
Antarctica

IceCube
Neutrino Observatory

1 km

SPICEcore
Borehole

1.5 km

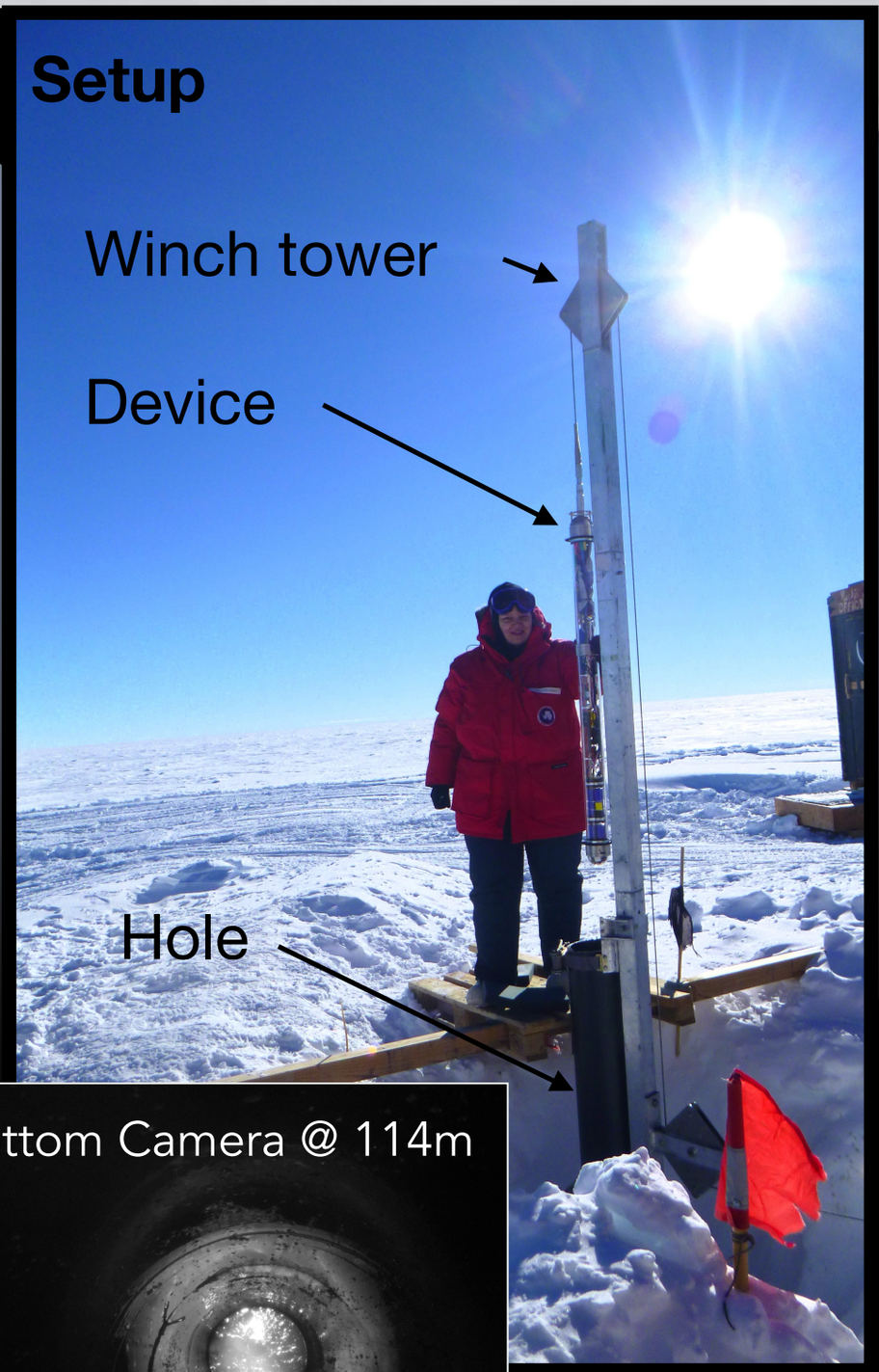
Ice layer tilt

350 m

650 m

1.75 km
⌀ 12,7 cm

Setup



Bottom Camera @ 114m

SPICEcore borehole

- filled with anti-freeze / drilling grease (Estisol)
- measurements in 2018 / 2019

Luminescence Logger

Goal

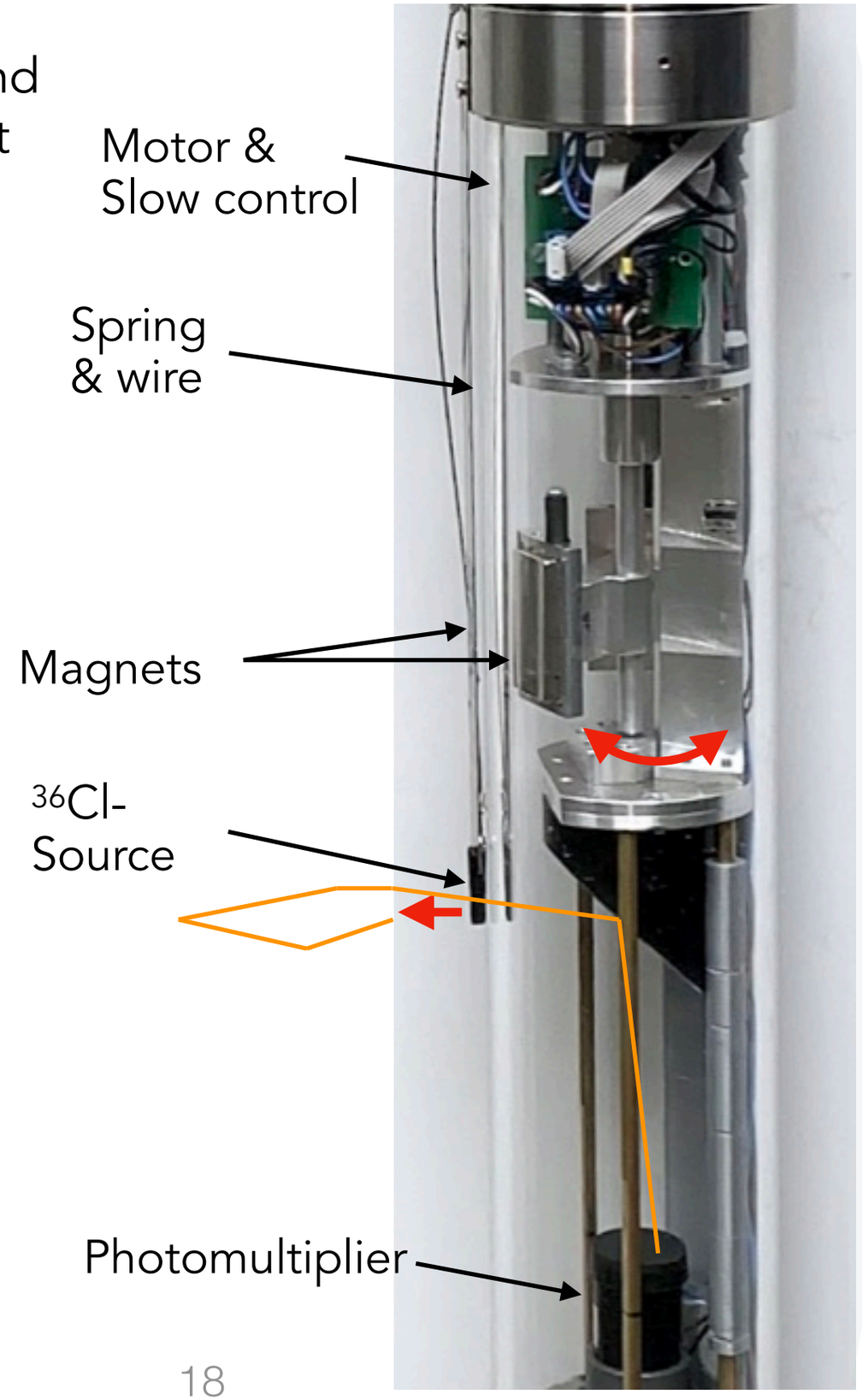
- irradiate ice with β-source and measure back-scattered light

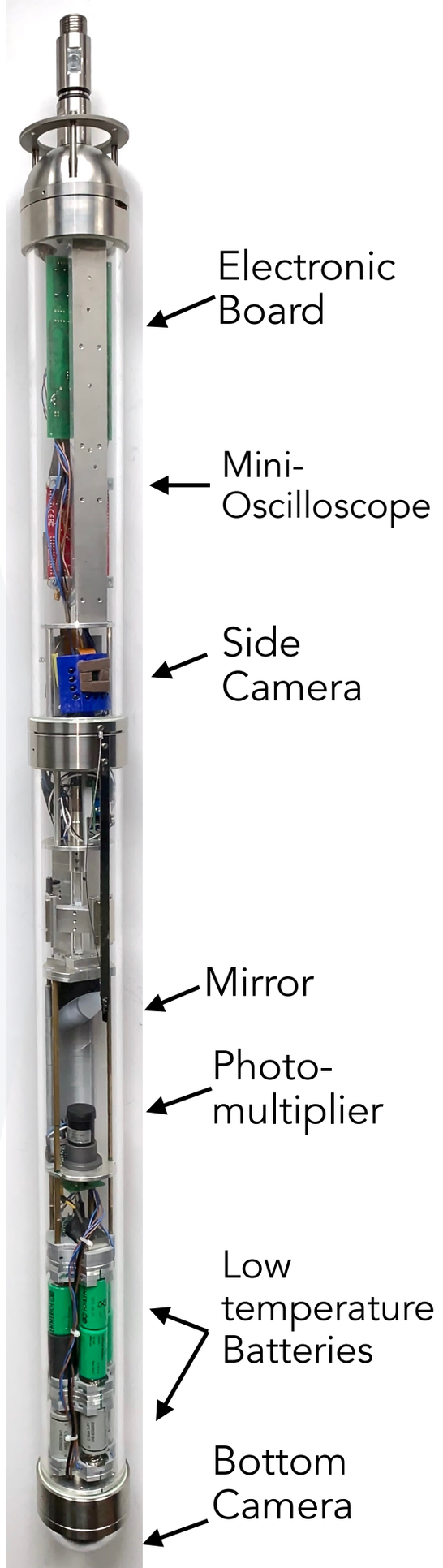
Method

- press source against ice
- guide scattered light onto photomultiplier

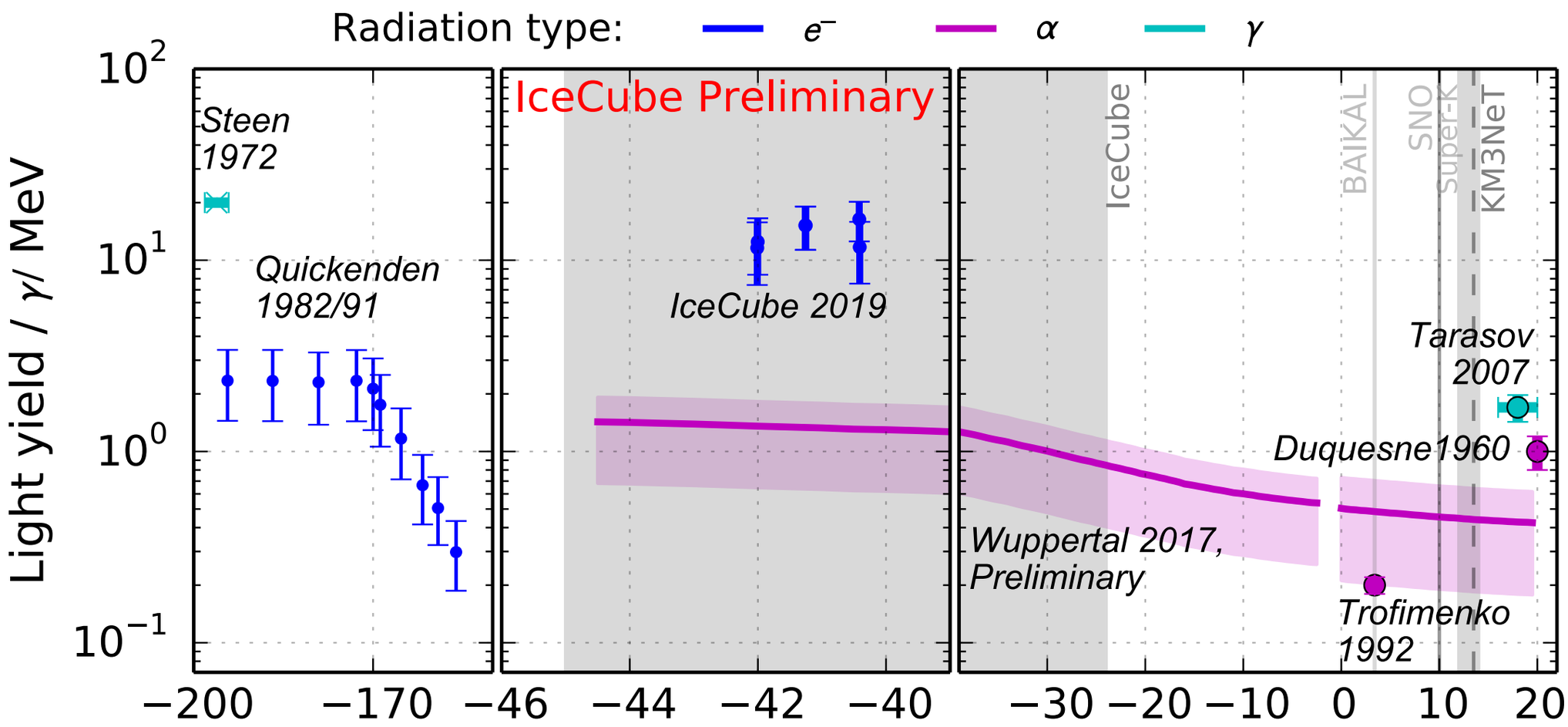
Details

- diameter: max 92 mm
- length: 1.30 m
- commercial mini USB-oscilloscope for readout
- light detection with photomultiplier tube
- several sensors: i.e. temperature, gyro, IR camera





Results: Luminescence light measurement



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Decay times

2.44 ± 2.07 ns
196.1 ± 39.1 ns
5.03 ± 0.06 µs
56.1 ± 6.29 µs

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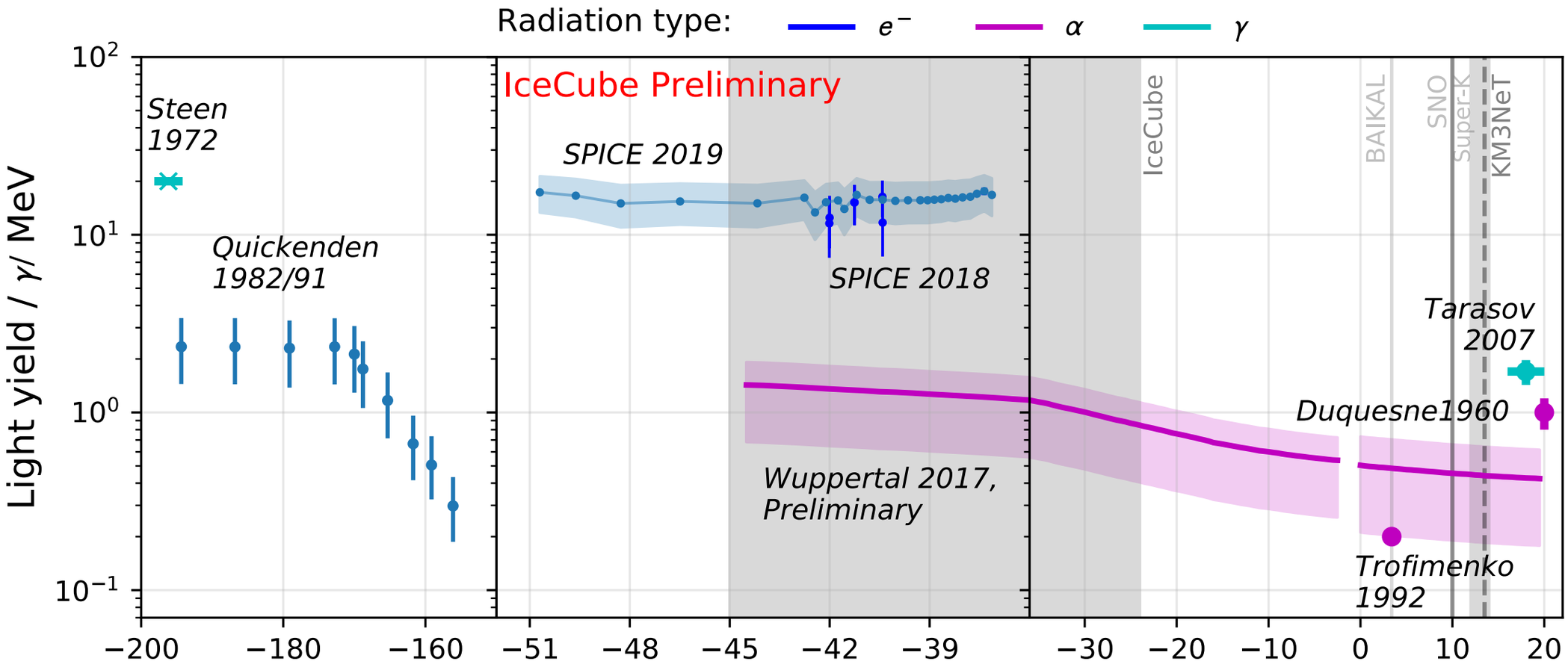
- "Trofimenko" is the only in-situ measurement, all others use cleaned water

Results: Luminescence light measurement



arXiv:1908.07231

Publication under preparation

Decay times

2.44 ± 2.07 ns
196.1 ± 39.1 ns
5.03 ± 0.06 µs
56.1 ± 6.29 µs

Note:

- sample quality varies significantly between measurements
- different radiation causes different amount of quenching

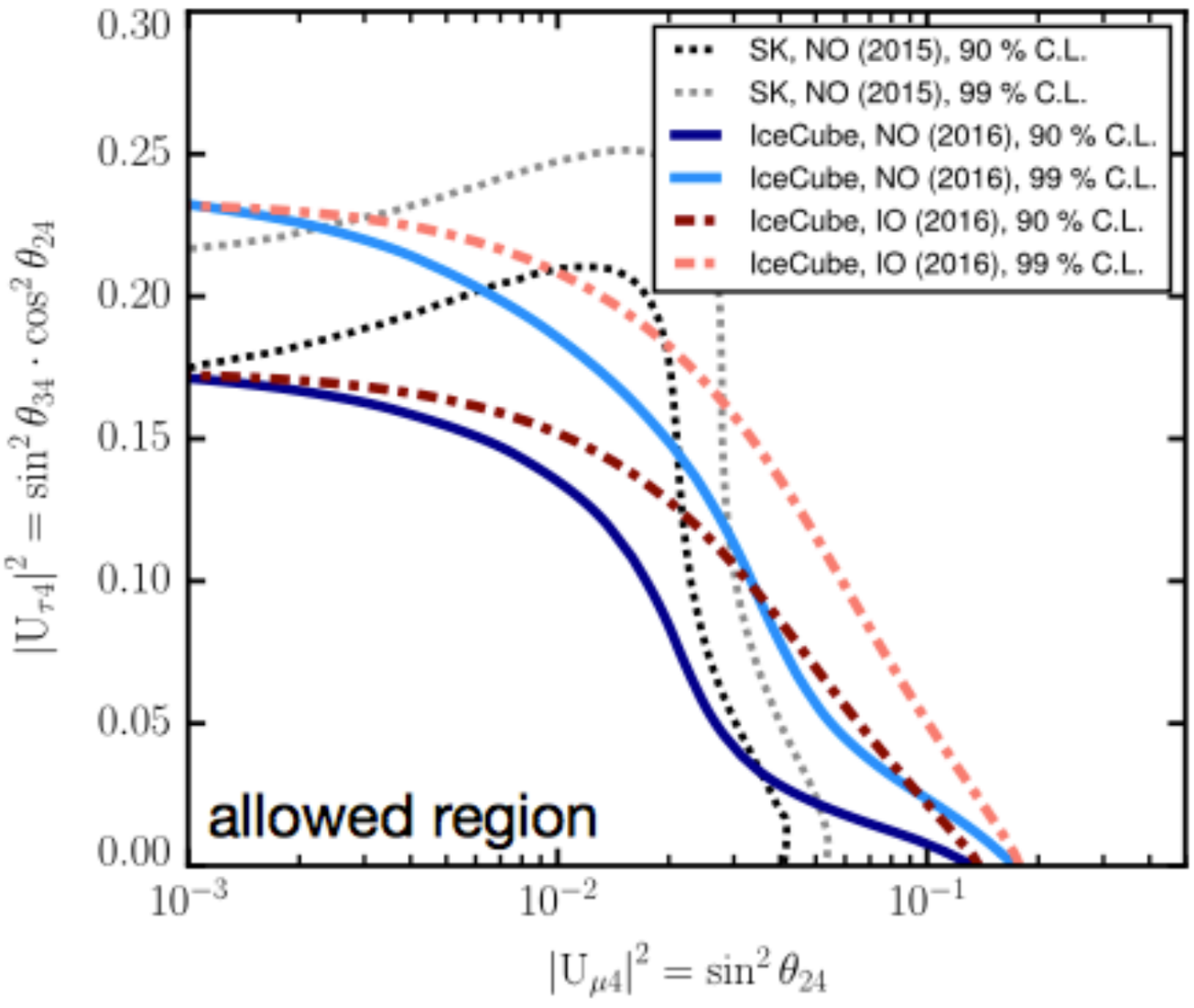
Comment:

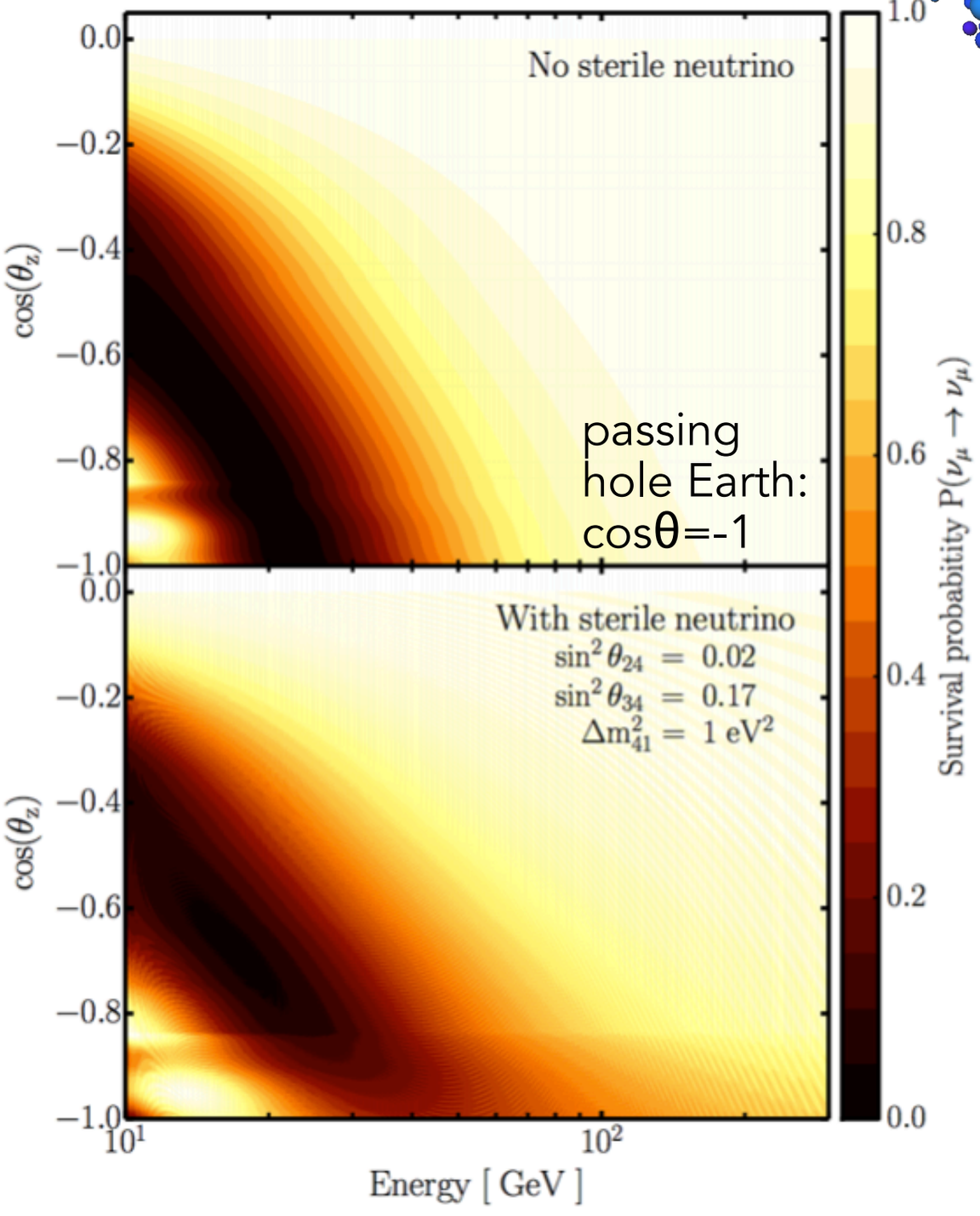
- uncertainties of new laboratory measurement originates from water quality
- "Trofimenko" is the only in-situ measurement, all others use cleaned water

Sterile neutrinos

Strategy

- for $\Delta m^2_{41} \sim 1\ eV^2$ sterile neutrino states produce a change in the matter potential



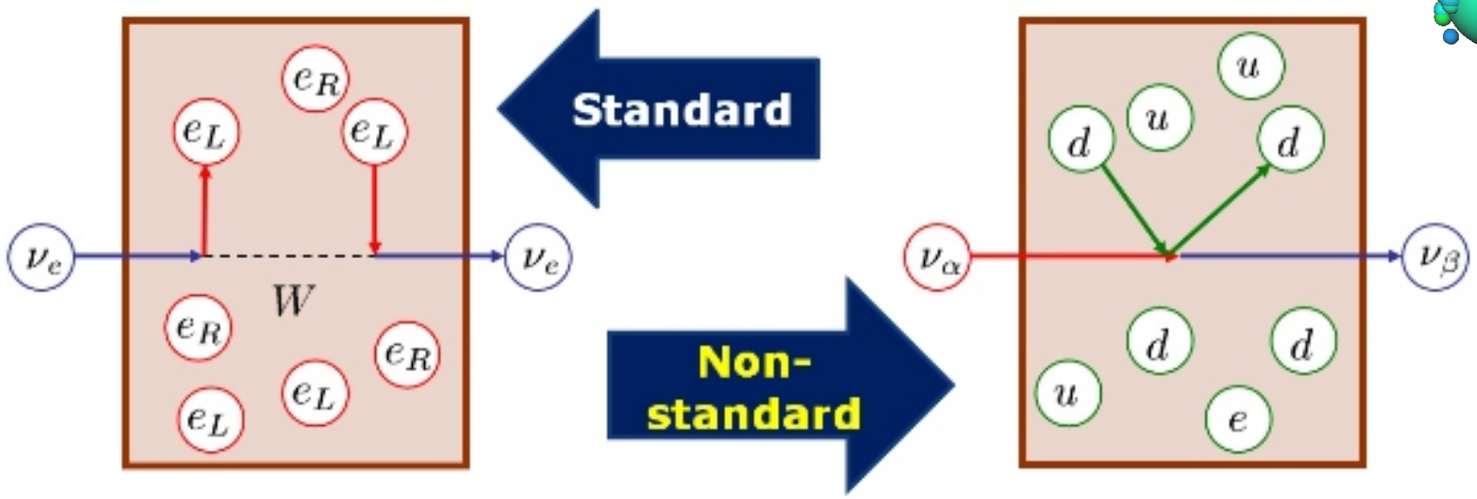


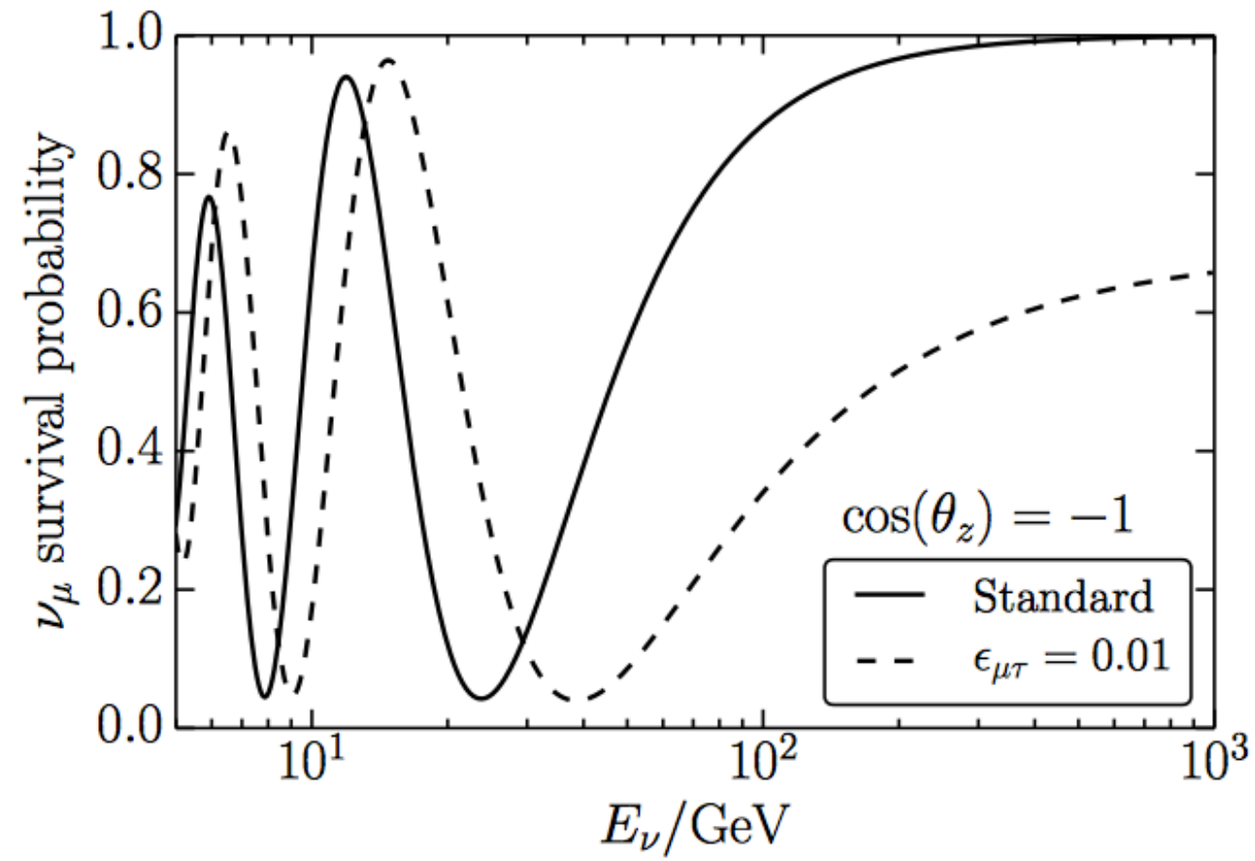
Phys. Rev. D95, 112002 (2017)

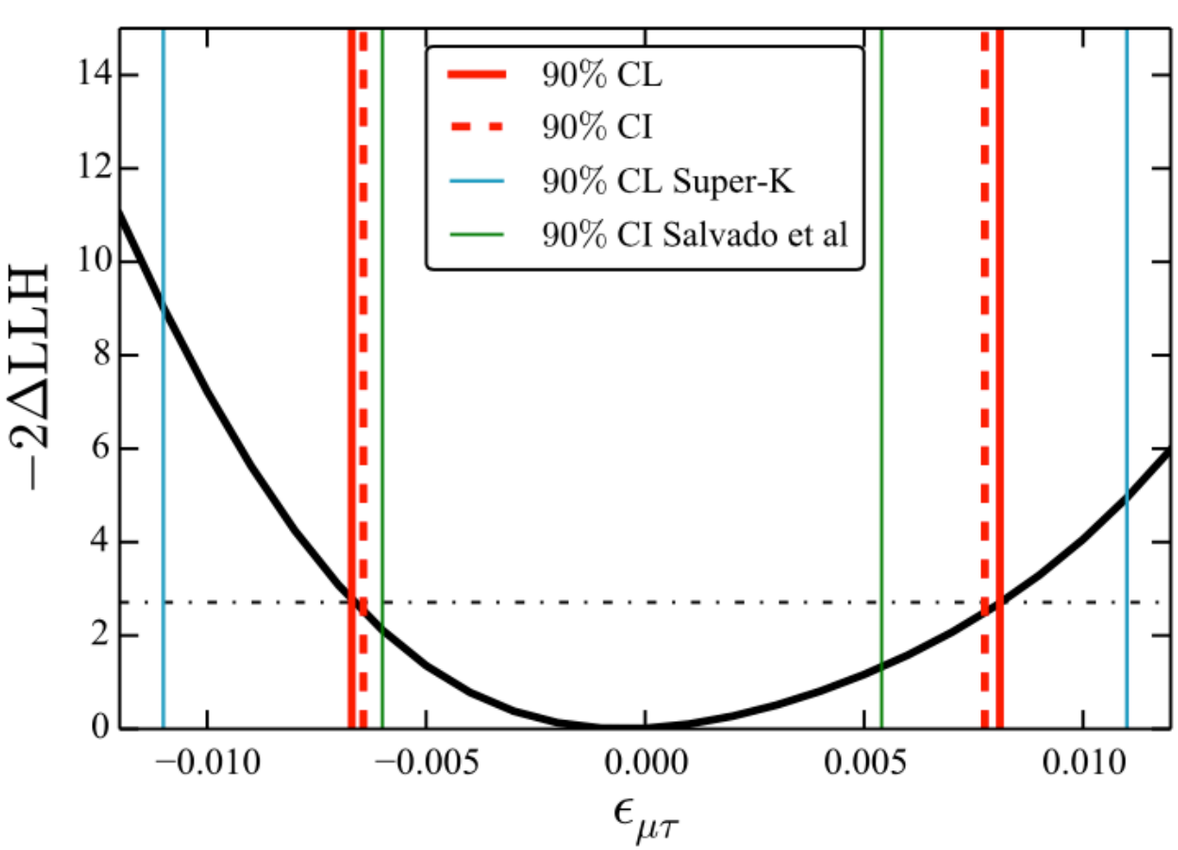
Non-standard neutrino interactions

Strategy

- additional potential by non-standard neutrino interactions changes oscillation pattern





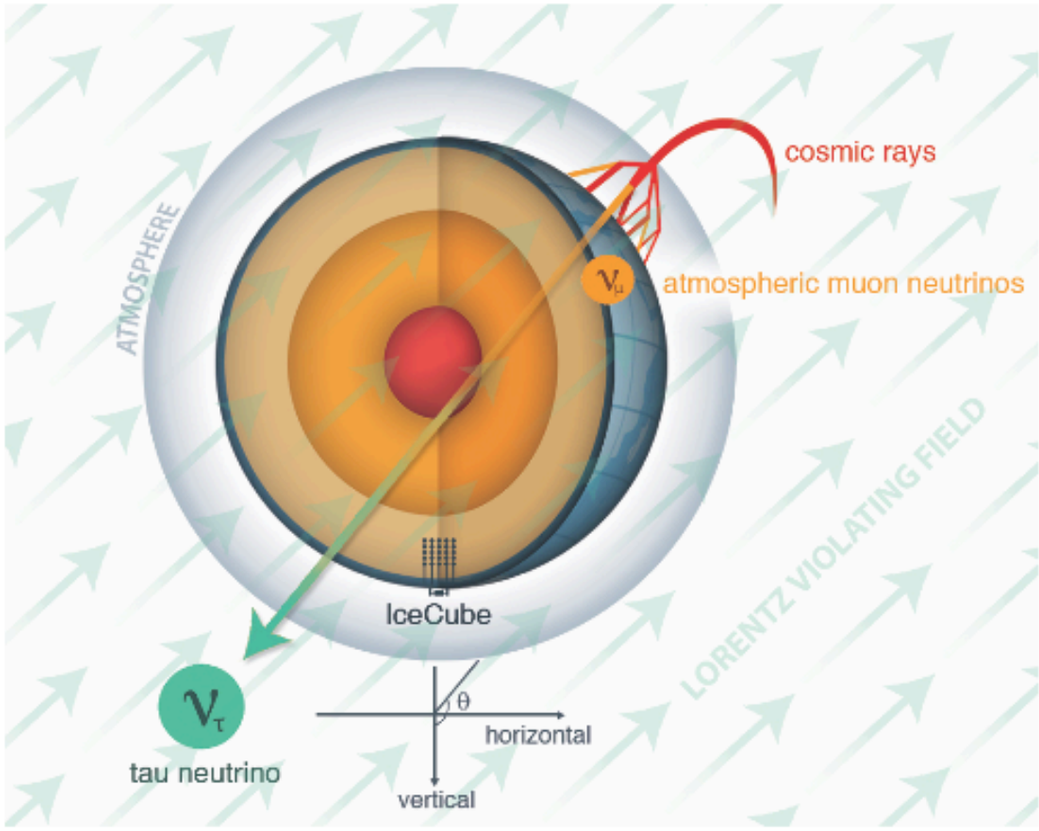


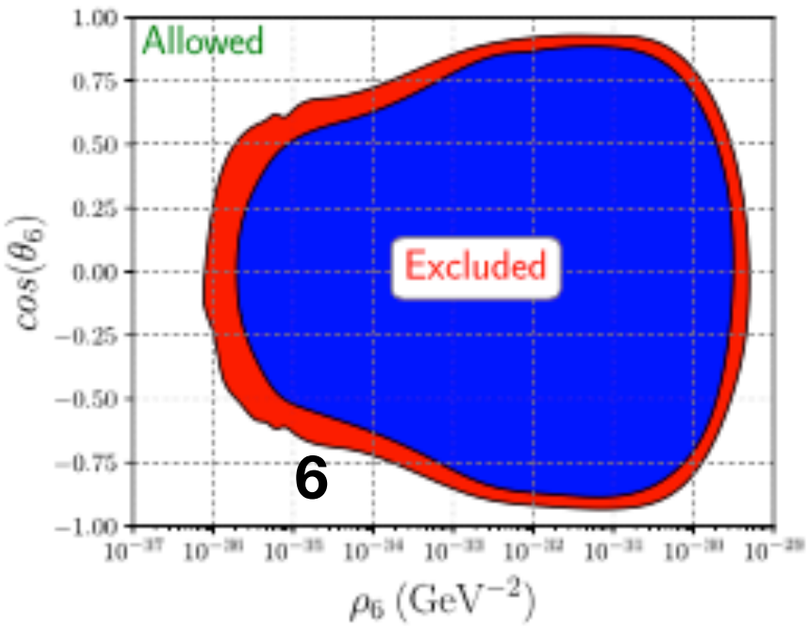
Phys. Rev. D 97, 072009 (2018)

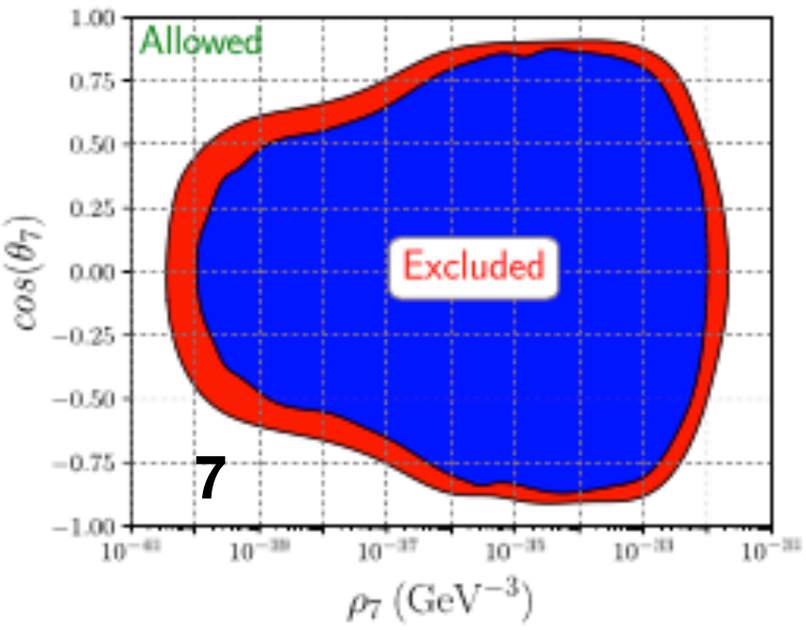
Lorentz Invariance Violation

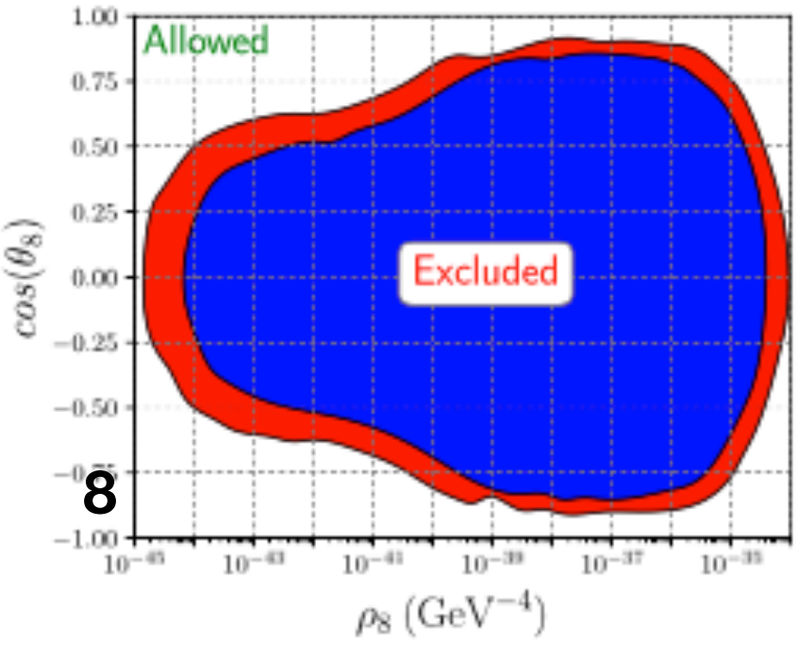
Strategy

- atmospheric neutrino sample
- Standard Model extension describes different LIV effects as operators of different dimension
- these change the neutrino oscillation probability
- signal: anomalous muon neutrino disappearance
- using 30k > TeV scale muon neutrinos
- result: best limits on LIV for higher dimensions





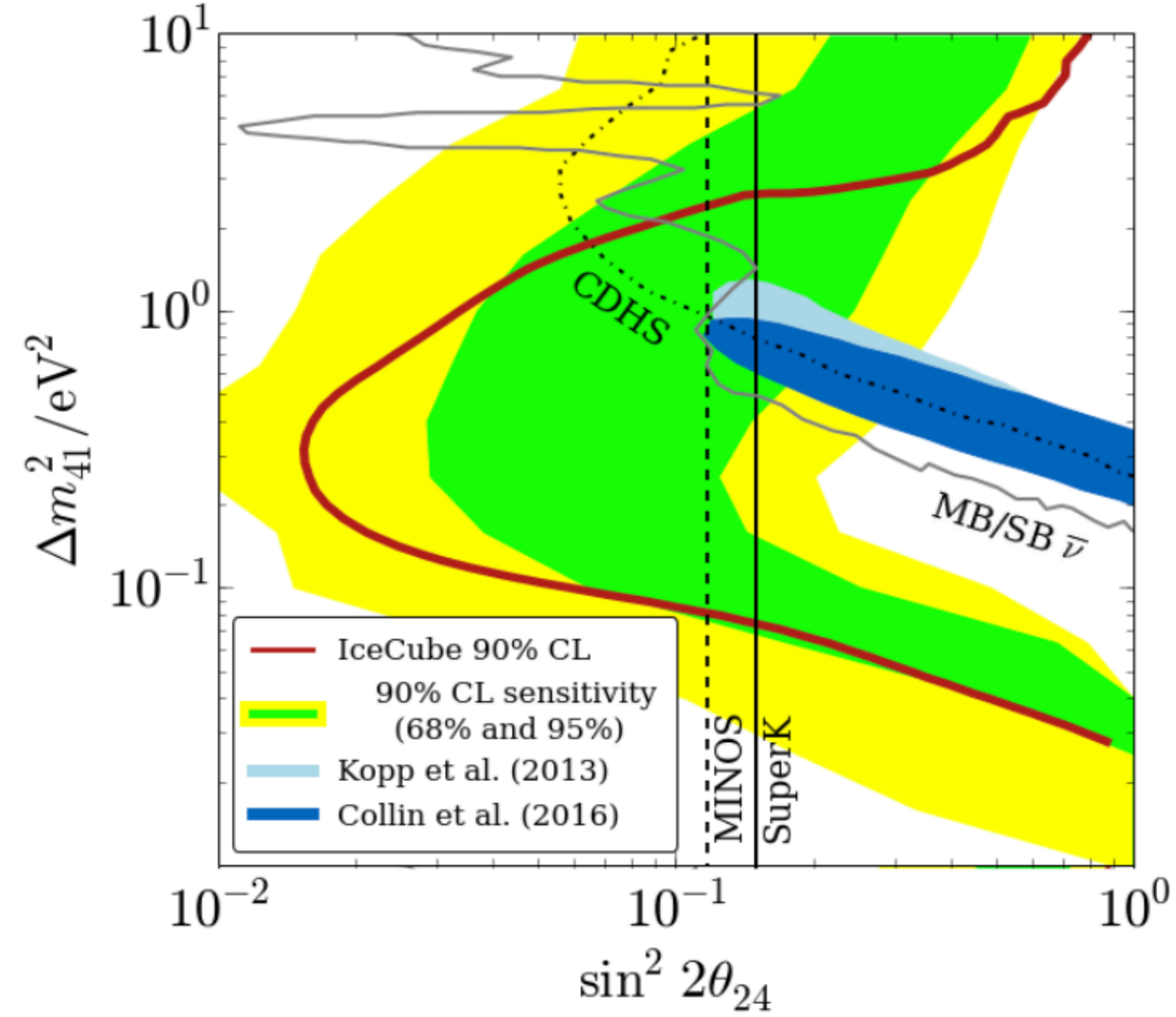


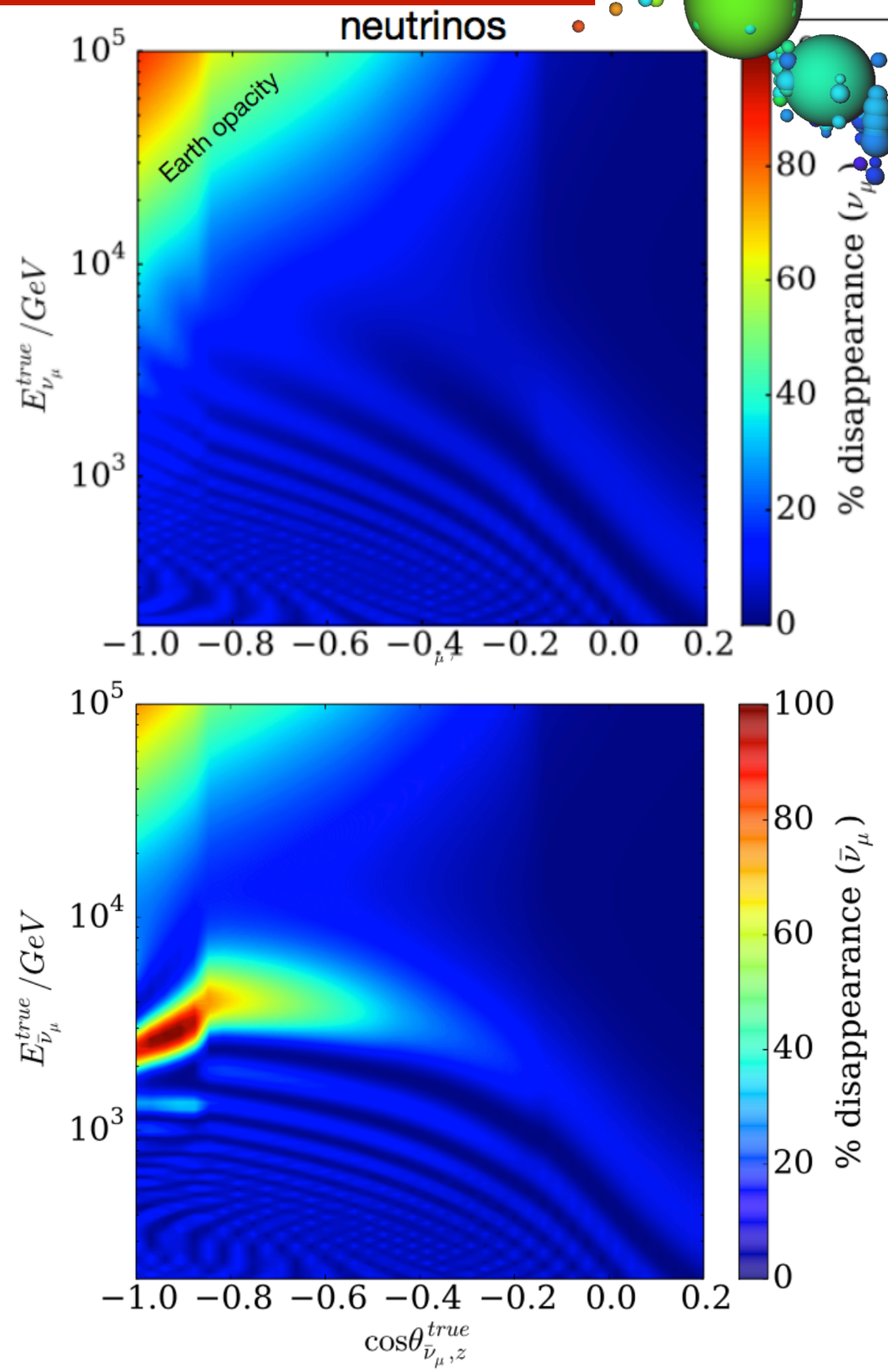


Sterile neutrinos at high energies

Strategy

- for $\Delta m^2_{41} \sim 1\ eV^2$ sterile neutrino states try to identify the resonant oscillation from ν_μ into ν_s





Phys. Rev. Lett. 117, 071801 (2016)